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A Systemic Approach Towards Circular Nutrient Flow Management in South American Metropolitan Areas: Linking Urban Metabolism and Strategic Urban Planning

Présentée par Alma FLEITAS GIRETT
Le 27 novembre 2024

Sous la direction de Tom WASSENAAR et Claudia PABÓN PEREIRA

Devant le jury composé de

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i. Research Summary

Cities and metropolitan areas are key to advancing sustainable development, a foundational principle of both urban metabolism and urban planning. Despite the potential synergy between these disciplines, their integration in real-world urban development processes remains challenging. This is particularly evident in the management of nutrient-containing materials such as fertilizers, food products, and organic waste. As cities grow and strive to improve their sustainability and resilience—especially in the face of climate change—their approaches to managing these "biological" flows are often fragmented and inadequate. This situation prompts the critical question: How can urban development strategies be designed to enable cities and regions to effectively and systematically incorporate nutrient circularity?

The first step in promoting nutrient circularity involves identifying and measuring the factors that influence nutrient-containing flow management in urban and regional development. These factors inform a city or region's capacity to implement effective strategies and enable comparisons over time or between areas. The assessment of these factors allows planners to identify system strengths and weaknesses for strategic resource management. The second step focuses on conducting a planning-oriented assessment, integrating urban metabolism and planning principles to evaluate these factors across multiple dimensions, generating insights for sustainable strategy development. Finally, incorporating diagnostic findings into ongoing strategic planning requires synthesizing these insights with existing policies and stakeholder interests, presenting them in a clear, accessible manner to facilitate stakeholder engagement in exploring future resource management scenarios.

This research aims to systemically analyze nutrient flows to enhance strategic planning processes towards increased nutrient circularity. The study's area of focus is South America due to its global significance in agrifood production and rapid urbanization. To address this main objective, this was broken down into three questions:

- What are the factors we need to consider when analyzing and managing nutrient containing flows, and how can we measure them?
- How can we assess these factors in a planning-oriented yet comprehensive way, at a metropolitan scale?
- How do we synthesize and present these findings to be functional and constructive for future strategic planning processes?

ARTICLE 1:

The transition to more sustainable nutrient management systems requires the integration of social, environmental, and economic dimensions from varying perspectives, while also incorporating local actors and values (Harder et al. 2021b; Poponi et al. 2022; Petit-Boix and

Leipold 2018; Gottinger et al. 2020). This study proposes a framework for measuring Nutrient Circularity Capacity (NCC), referring to a context's potential to develop and implement circular nutrient initiatives, based on existing characteristics. The framework first defines the material and organizational characteristics that influence NCC and then selects indicators to measure them. To assess NCC, we applied this tool to South American MAs.

METHODOLOGY: Assessing the capacity for nutrient circularity involved evaluating local conditions that either support or hinder the transition to circular management systems. A four-step methodology was established: a) identification of environmental, technical, economic, social, and political factors influencing nutrient circularity, b) selection of indicators to assess these factors, c) collection and analysis of local data to inform the indicators, and d) scoring values to compare nutrient circularity capacity (NCC) across metropolitan areas. A literature review using the Scopus database and EU publications focused on terms like “enablers,” “drivers,” “barriers,” and “obstacles” related to “circular economy,” “circular bioeconomy,” and “sustainable resource management.” The review narrowed down recent, relevant articles (2017–2021), resulting in 21 key documents identifying nearly 400 elements across environmental, socio-economic, and political-legal dimensions. These elements were synthesized into a three-level hierarchy—Central Themes, Influencing Factors, and Indicators—streamlining overlaps and gaps, and aligning concepts with agri-food system specifics, such as agricultural activities, technologies, and urban infrastructure.

Next, since IFs are not directly observable or measurable, proxy variables were identified. Still, these were found to be too broad for the objectives of this study and were therefore again linked to another set of more well-known, pragmatic variables called possible indicators, without contemplating restrictions of geographic setting or availability. Next, international databases and indexes were consulted to develop a list of relevant, existing indicators that could also be linked to the IF. Considering the vast possibility of variables and indicators that could derive from these processes, a multi-criteria analysis assessed the possible indicators with pre-selected criteria that could allow the selection of “top possible indicators”. Finally, the highest-scoring possible indicators were selected, aiming for a selection short enough to allow a feasible analysis yet long enough to include as many influencing factors as possible. Once the final selection of indicators was established, this list was compared to the list of existing indicators that was previously developed. The indicators that could be matched to existing ones were further evaluated to assess credibility, feasibility, and salience. Alternatively, indicators that couldn’t be matched were re-formulated to link their original compositional data to existing information that could then be re-processed to create a similar, satisfactory indicator. Existing indicator values were collected from their sources, while missing data were sourced from surveys, statistical databases, government reports, waste treatment companies, and local experts. Thresholds for "high," "medium," and "low" were set for each indicator to compare

nutrient circularity capacity (NCC) among South American metropolitan areas (SAMAs), enabling a simple scoring system (low=0, medium=1, high=2). A non-exhaustive sample of SAMAs, covering the 10 countries with large metropolitan areas per OECD criteria, was selected to reflect geographic diversity and population size.

RESULTS: Twelve Influencing Factors (IFs) were identified across four central themes: Material Flow Potential, Food & Feed Value Chain Characteristics, Knowledge Base, and Institutional Support. These IFs were linked to 33 proxy variables and 39 possible indicators, which were evaluated through a multi-criteria analysis, yielding three rankings of feasible, representative nutrient circularity indicators. From these rankings, 11 indicators were selected, covering two-thirds of the IFs. These 11 were then compared to 56 existing indicators from international databases. Six were successfully matched, while the remaining five, related to local material capacity, were re-formulated due to issues with scale or outdated information. After selecting indicators, data was collected and processed for South American metropolitan areas (SAMAs).

Indicator values reveal that Uruguay had the highest organizational capacity among South American countries, driven by strong government support for innovation, knowledge creation, and circular economy policies. Paraguay and Bolivia ranked lowest, with minimal investment in knowledge creation and no circular economy policies. Santiago, Montevideo, and Santa Cruz de la Sierra demonstrated the highest material capacities, while Asunción, Sao Paolo, and Lima had the lowest, due to limited agricultural activities and poor waste management systems. Montevideo led in nutrient circularity capacity (NCC) with 14 out of 20 points, while Asunción lagged behind with only 3 points. The average NCC score across all areas was 9, with a median of 10.

DISCUSSION: This assessment of factors influencing the transition to circular nutrient management systems appears to be the first of its kind for South America, both at national and metropolitan levels. Studies on sustainable transitions and nutrient circularity in the region are rare, and while interest in circular economy research is growing, a major barrier to implementation is the lack of consensus on the concept's principles and applicability (Betancourt Morales and Zartha Sossa 2020). These authors also emphasize the need for a simplified conceptual framework that accommodates the cultural and economic differences between Europe, where the concept is widely studied, and Latin America. This study synthesized hundreds of factors into a framework of 4 Central Themes, 12 Influencing Factors, and 11 Indicators, providing a practical tool for any context. Additionally, these concepts were made measurable through indicators based on preexisting, yet underutilized, data.

Nutrient circularity capacity (NCC) varied among South American metropolitan areas (SAMAs), with no area leading or lagging in all aspects. Montevideo, Uruguay, had the highest NCC, while Asunción, Paraguay, ranked the lowest, though most SAMAs showed similar overall

levels. Montevideo's high NCC aligns with its GDP per capita, suggesting economic factors may be a key barrier for countries like Paraguay and Bolivia. However, mid-level economies like Bogotá and Quito reached higher NCC levels due to strong organic waste treatment. Peri-urban agriculture, innovation investment, and effective environmental management were key drivers of higher NCC across SAMAs.

ARTICLE 2:

Transitioning to sustainable nutrient management requires systemic change and strategic planning (Medeiros and van der Zwet 2020). UN Habitat's strategic urban planning emphasizes a systematic approach, prioritizing key issues through consensus and analysis (UN Habitat, 2007). Initial assessments are vital for strategy formulation, particularly in addressing the diverse factors influencing nutrient circularity (Arciniegas et al., 2019). However, integrating these factors is challenging, as urban metabolism and urban planning often operate separately. This gap results in institutions lacking critical insights for comprehensive policy development (Binder, 2007; Yetano Roche et al., 2014). This research aims to address this gap by developing a multidimensional strategic diagnostic framework, applicable to real-world contexts, that can contribute to strategic urban planning processes. The framework was applied to the Metropolitan Region of Santiago, a regional forerunner in nutrient circularity capacity that can serve as a representative case study for urban areas facing similar challenges (Fleitas Girett et al., 2023).

METHODOLOGY: This research follows the UN Our City Plans toolbox, specifically Block D "Analysis and Diagnosis" of Phase 1 "Assessment" (Appendix A), to align with urban planning processes. The diagnostic process begins with desk and field research, followed by analysis and validation. Stakeholder participation is key, with semi-structured interviews conducted with public, private, and civil actors for data collection and validation. Actors were initially identified through relevant national or regional policy documents, then expanded using the snowball method during interviews. Interviews were conducted in person or via Zoom, recorded, and transcribed using Amberscript (interview guidelines in Appendix B).

The system's spatial and temporal scope is defined to balance comprehensiveness, feasibility, and functionality. This involves reviewing regional agri-food system characteristics and data availability, considering institutional factors, and outlining strategic objectives. Analysis boundaries are set to ensure the study's focus is aligned with local goals, identifying primary activities within subsystems and key nutrient flows between them. Activities responsible for 50% or more of the total within each subsystem are prioritized, with nutrient flows identified through scientific literature, technical reports, and PRTR data. The system is then represented in a diagram showing the agri-food-waste subsystems, primary activities, and key nutrient flows.

This research takes a multi-dimensional approach based on the Ecopolis framework (Tjallingii, 1995), incorporating spatial, material, and social dimensions. The spatial dimension addresses the territory's agri-food-waste system activities, the material dimension focuses on nutrient flows, and the social dimension considers the roles, concerns, and interactions of relevant actors.

First, basic spatial data such as administrative boundaries and land use are gathered from local databases and processed using GIS software. The analysis focuses on strategically significant "detrimental" and "opportunity" flows, with priority given to nutrient-containing flows in three categories: a) waste flows from all subsystems directed to treatment, final disposition, or lost to the environment; b) outputs reused in crop, animal, or food production; and c) input products in crop and animal production. Nutrient content in output materials is grouped into plant tissue, animal tissue, or wastewater treatment plant (WWTP) sludge, with nitrogen, phosphorus, and potassium levels calculated using spreadsheet software based on literature, technical reports, and local data. In addition to interviews, official websites of relevant organizations are reviewed to identify their objectives, areas of focus, and collaborations. Stakeholders are characterized by their connection to the agri-food-waste subsystems, their roles as stakeholders (following Bijon et al., 2023), and their main priorities considering their goals and responsibilities. To assess actor connections, a social network matrix is created (Borgatti et al., 2009; Ghinoi et al., 2020), focusing on whether two actors regularly collaborate on managing key material flows, while respecting the analytical boundaries set earlier in the diagnostic.

Finally, two indicators were proposed to integrate findings from the multidimensional analysis and assess key concerns of nutrient circularity strategies: a) reducing linear waste management in urban areas to minimize resource losses and environmental contamination, and b) increasing the reintegration of secondary materials into production processes to reduce resource extraction and enhance regional food security.

RESULTS: The diagnostic framework was validated in the Metropolitan Region of Santiago de Chile (MRSC), focusing on activities and nutrient flows within its six provinces and 52 communes. Data from 2021 was used, supported by a recent agricultural survey. In addition to a literature review, 34 semi-structured interviews with government, private, civil, and academic actors were conducted. A system diagram mapped the main agri-food-waste activities and nutrient flows, revealing urban-centered consumption activities, while food production and waste treatment were concentrated in peripheral areas. Fruit production, particularly wine grapes, dominated cropland (59%), with cereal crops and pig and broiler farms concentrated in Melipilla province.

The flow analysis quantified nitrogen (N), phosphorus (P), and potassium (K) flows in the region, visualized through hybrid Sankey Diagrams. In the MRSC, nutrient demand is driven

by urea, which dominates crop production, especially for cereals and vegetables, while fruit trees rely heavily on potassium fertilizers with limited phosphorus use. Data on bio-inputs like compost is scarce, and animal feed is largely dependent on imported soy, maize, and wheat, supplemented with some local additives. On the supply side, crop and animal production generate unprocessed waste, while food production produces raw byproducts and wastewater treatment plant (WWTP) sludge. Farmers often undervalue manure, leading to nutrient accumulation and environmental losses. Households contribute significantly to nutrient losses through landfilled waste, while treatment facilities release processed materials such as compost and sludge. The MRSC functions as a nutrient sink, with most resources used once. Nutrient surpluses decrease when considering imported animal feed, though excesses vary across zones, and phosphorus pollution in the Maipo River is likely linked to WWTP effluents. Nutrient circularity indicators provided a comparable metric for urban nutrient recovery and agricultural reuse at the regional level. The RUN indicator scores, converted to percentages, showed recovery rates of 78% for nitrogen, 85% for phosphorus, and 52% for potassium, with a combined recovery score of 72%. This high score is driven by wastewater treatment, with most urban outputs directed to wastewater treatment plants. Improving the indicator requires increasing the recovery of organic solid waste, such as food and garden waste, currently sent to landfills.

In the people dimension, 45 key actors were identified and classified by role type (material or influential) and primary concern. The analysis found 12 material actors, 28 influential actors, and 5 performing both roles. Regarding nutrient recovery and reuse, 21 actors focused on nutrient reuse in agriculture, 16 on urban nutrient recovery, and 8 on both.

DISCUSSION: The Metropolitan Region of Santiago de Chile (MRSC) faces significant challenges in meeting nutrient demands due to its reliance on imports and lack of soil nutrient control. The diagnostic highlights a disconnect between rural and urban areas and across sectors, pointing to the need for integrated resource management strategies and better collaboration among stakeholders.

Obstacles such as limited awareness, distrust in recycled products, and regulatory barriers hinder nutrient recovery from sources like wastewater treatment plant (WWTP) sludge and animal slurry. The absence of circular agriculture in university curricula further widens the knowledge gap, limiting professionals capable of advising on organic fertilizer use. Despite notable nutrient losses, especially from organic waste, the RUN indicator shows considerable recovery potential. In agriculture and urban sanitation, efforts to minimize nitrogen loss reduce the need for active nitrogen management. However, limited municipal budgets for waste management exacerbate logistical and technological constraints. Research and development, concentrated in the private sector, further impedes accessibility and dissemination of innovative solutions.

This research offers an adaptable diagnostic framework to support regional nutrient circularity, helping local planners identify challenges, opportunities, and synergies across urban-rural and sectoral boundaries. By focusing on primary activities and nutrient flows, the diagnostic simplifies interpretation and provides practical, context-specific insights. Mapping the spatial distribution of activities helps visualize nutrient flows and identify opportunities for collaboration and infrastructure planning. The flow analysis clarifies how nitrogen, phosphorus, and potassium (NPK) are demanded, lost, or recovered, enabling targeted strategies to reduce losses and increase recovery, which improves self-sufficiency and food security. Additionally, the framework helps identify key actors for inclusion in nutrient circularity strategies and strengthens links between aligned stakeholders.

ARTICLE 3

In this work, we go one step further, aiming to bridge the gap between a territorial nutrient-flow diagnosis to scenario building through the development of narratives. We propose a framework that integrates diagnosis insights with stakeholder inputs and local strategies to construct these narratives, providing an evidence-based and contextualized nutrient-circularity perspective for current and future scenario-building processes and vision exploration exercises that occur in the context of circular urban development. Like the previous diagnostic framework, we have applied these tools to the Metropolitan Region of Santiago, a regional leader in nutrient circularity capacity.

METHODOLOGY: The framework proposed in this study aims to connect the analysis and diagnostic step with the scenario building step through narratives, building off the “Our City Plans” framework proposed by UN Habitat (2022) and the SAS approach proposed by Alcamo (2005). The development of scenario narratives is comprised of three main tasks: contextualization of data, synthesizing of findings, and constructing the narratives themselves. The first and second task focus on gathering and categorizing information related to nutrient-containing flow management from three sources: the strategic multi-dimensional diagnosis, main policy documents, and stakeholder inputs. This task involves the development of focal questions, collection of stakeholder feedback, and lastly, the identification and connection of narrative elements.

RESULTS: The policy review identified two overarching goals related to nutrient-containing flows: 1) increasing the recycling of municipal organic waste, and 2) promoting sustainable agricultural production. Stakeholder insights on goals, barriers, strategies, and priorities were organized, highlighting key challenges. In terms of material flow potential, insufficient waste treatment infrastructure, high transportation costs, and regulatory restrictions were noted as major barriers. Value chain challenges included a lack of awareness, trust in secondary

materials, and collaboration between sectors, as well as financial and technical limitations. The local knowledge base was hindered by a lack of independent research, training on circular practices, and influence from mineral fertilizer companies. Institutional challenges included outdated regulations, insufficient waste management protocols, and uneven resource distribution among municipalities.

Variables were identified from policy documents, stakeholder inputs, and the diagnostic framework, then categorized by subsystem, influencing factor, and nutrient circularity (NC) objectives. Overlaps and gaps in challenges, opportunities, and strategies were linked to shared sectors or interests to form strategic proposals. Three focal questions were developed to explore potential solutions:

- What if composting capacity is increased and green urban areas are maintained with nutrients recovered from municipal waste?
- What if animal residue nutrients are used more efficiently and applied to more crops?
- What if WWTP technologies improved, enabling sludge nutrients to be applied to crops like fruits and vegetables?

These questions were presented to stakeholders in a workshop in Santiago, Chile, where feedback was collected. The first two questions addressed shared goals from the policy review, while the third expanded beyond current policy, integrating a systemic view based on diagnostic findings. The resulting narratives bridged gaps across subsystems and influencing factors, addressing areas not yet prioritized in existing plans.

DISCUSSION: The proposed framework connects the assessment phase to the planning phase, offering a rigorous model that other cities and planning bodies can adopt to enhance their processes. It promotes a systemic perspective essential for nutrient circularity, encouraging actors to explore alternative strategies that go beyond current practices. By providing a holistic view, the framework supports informed decision-making and fosters stakeholder engagement (Alcamo et al. 2005; Mallampalli et al. 2016). Grounding the narratives in multidimensional analysis, stakeholder insights, and core principles of nutrient circularity helps avoid incomplete solutions, driving broader systemic transformations. This approach enables the development of integrated strategies for managing nutrient-containing flows, essential for urban and regional sustainability. In cities like the Metropolitan Region of Santiago de Chile (MRSC), where circular planning is already underway, these findings can help evaluate and adapt existing plans, offering alternatives that push toward deeper systemic circularity.

In conclusion, this research presents a robust framework for advancing nutrient circularity in South America by systemically analyzing nutrient flows to enhance strategic planning. It begins

by establishing a clear understanding of nutrient circularity and developing a method to measure it at a territorial level, offering valuable insights into the factors that shape nutrient flow management. Building on this foundation, the framework guides the execution of a comprehensive, multidimensional diagnostic that remains strategic, balancing detailed analysis with practical applicability. This diagnostic is then synthesized with local goals and concerns to construct actionable narratives that inform future planning processes. By addressing the core factors influencing nutrient flows, the study provides a structured, comprehensive approach to assessment, as well as facilitating the translation of findings into strategic insights for decision-makers and planners through strategic planning processes.

ii. Résumé de la recherche

Les villes et les zones métropolitaines jouent un rôle clé dans la promotion du développement durable, un principe fondamental de la métabolisation urbaine et de la planification urbaine. Bien que ces deux disciplines puissent être complémentaires, leur intégration dans les processus réels de développement urbain reste difficile. Cela est particulièrement évident dans la gestion des matières contenant des nutriments, telles que les engrais, les produits alimentaires et les déchets organiques. À mesure que les villes se développent et cherchent à améliorer leur durabilité et leur résilience, notamment face aux changements climatiques, leurs approches de gestion de ces flux "biologiques" restent souvent fragmentées et inadéquates. Cette situation pose une question critique : comment concevoir des stratégies de développement urbain permettant aux villes et aux régions d'intégrer efficacement et systématiquement la circularité des nutriments ? La première étape de la promotion de la circularité des nutriments consiste à identifier et à mesurer les facteurs influençant la gestion des flux contenant des nutriments dans le développement urbain et régional. Ces facteurs déterminent la capacité d'une ville ou d'une région à mettre en œuvre des stratégies efficaces et permettent des comparaisons dans le temps ou entre les zones. L'évaluation de ces facteurs permet aux planificateurs d'identifier les forces et les faiblesses du système pour une gestion stratégique des ressources. La deuxième étape consiste à réaliser une évaluation orientée vers la planification, intégrant les principes de la métabolisation urbaine et de la planification pour évaluer ces facteurs à travers plusieurs dimensions, générant ainsi des idées pour le développement de stratégies durables. Enfin, intégrer les conclusions diagnostiques dans la planification stratégique en cours nécessite de synthétiser ces idées avec les politiques existantes et les intérêts des parties prenantes, en les présentant de manière claire et accessible pour faciliter l'engagement des parties prenantes dans l'exploration de scénarios futurs de gestion des ressources. Cette recherche vise à analyser de manière systémique les flux de nutriments pour améliorer les processus de planification stratégique en vue d'accroître la circularité des nutriments. La zone d'étude se concentre sur l'Amérique du Sud en raison de son importance mondiale dans la production agroalimentaire et de son urbanisation rapide. Pour répondre à cet objectif principal, celui-ci a été décliné en trois questions :

- Quels sont les facteurs à prendre en compte lors de l'analyse et de la gestion des flux contenant des nutriments, et comment pouvons-nous les mesurer ?
- Comment évaluer ces facteurs de manière complète tout en étant orienté vers la planification, à l'échelle métropolitaine ?
- Comment synthétiser et présenter ces résultats de manière fonctionnelle et constructive pour les processus futurs de planification stratégique ?

ARTICLE 1 :

La transition vers des systèmes de gestion des nutriments plus durables nécessite l'intégration des dimensions sociales, environnementales et économiques sous différents angles, tout en incorporant les acteurs locaux et leurs valeurs (Harder et al. 2021b; Poponi et al. 2022; Petit-Boix et Leipold 2018; Gottinger et al. 2020). Cette étude propose un cadre pour mesurer la Capacité de Circularité des Nutriments (CCN), faisant référence au potentiel d'un contexte à développer et mettre en œuvre des initiatives de circularité des nutriments, sur la base de caractéristiques existantes. Ce cadre définit d'abord les caractéristiques matérielles et organisationnelles qui influencent la CCN, puis sélectionne des indicateurs pour les mesurer. Pour évaluer la CCN, nous avons appliqué cet outil aux aires métropolitaines sud-américaines. MÉTHODOLOGIE : L'évaluation de la capacité de circularité des nutriments impliquait l'évaluation des conditions locales qui soutiennent ou entravent la transition vers des systèmes de gestion circulaires. Une méthodologie en quatre étapes a été établie : a) identification des facteurs environnementaux, techniques, économiques, sociaux et politiques influençant la circularité des nutriments, b) sélection d'indicateurs pour évaluer ces facteurs, c) collecte et analyse des données locales pour alimenter les indicateurs, et d) attribution de scores pour comparer la capacité de circularité des nutriments (CCN) entre les aires métropolitaines. Une revue de la littérature à partir de la base de données Scopus et de publications de l'UE s'est concentrée sur des termes tels que "facilitateurs", "facteurs moteurs", "obstacles" et "entraves" liés à "l'économie circulaire", "la bioéconomie circulaire" et "la gestion durable des ressources". La revue a sélectionné des articles récents et pertinents (2017-2021), aboutissant à 21 documents clés identifiant près de 400 éléments couvrant les dimensions environnementale, socio-économique et politico-juridique. Ces éléments ont été synthétisés dans une hiérarchie à trois niveaux — Thèmes centraux, Facteurs influents et Indicateurs — simplifiant les chevauchements et lacunes, et alignant les concepts sur les spécificités du système agroalimentaire, telles que les activités agricoles, les technologies et les infrastructures urbaines.

Ensuite, comme les FI ne sont ni directement observables ni mesurables, des variables de substitution ont été identifiées. Cependant, elles se sont révélées trop larges pour les objectifs de cette étude et ont donc été reliées à un autre ensemble de variables plus connues et pragmatiques, appelées indicateurs possibles, sans tenir compte des restrictions liées au contexte géographique ou à la disponibilité. Ensuite, des bases de données internationales et des indices ont été consultés pour établir une liste d'indicateurs existants pertinents pouvant également être liés aux FI. Compte tenu des vastes possibilités de variables et d'indicateurs pouvant découler de ces processus, une analyse multicritère a évalué les indicateurs possibles en utilisant des critères prédéfinis permettant de sélectionner les "meilleurs indicateurs possibles". Enfin, les indicateurs possibles les mieux notés ont été sélectionnés, dans le but

de constituer une sélection suffisamment courte pour permettre une analyse réalisable, mais suffisamment longue pour inclure autant de facteurs influents que possible. Une fois la sélection finale des indicateurs établie, cette liste a été comparée à la liste des indicateurs existants précédemment élaborée. Les indicateurs qui pouvaient être associés à des indicateurs existants ont été évalués pour vérifier leur crédibilité, faisabilité et pertinence. Alternativement, les indicateurs qui ne pouvaient pas être associés ont été reformulés pour relier leurs données de composition initiales à des informations existantes qui pouvaient ensuite être retraitées pour créer un indicateur similaire et satisfaisant. Les valeurs des indicateurs existants ont été collectées à partir de leurs sources, tandis que les données manquantes ont été obtenues à partir d'enquêtes, de bases de données statistiques, de rapports gouvernementaux, d'entreprises de traitement des déchets et d'experts locaux. Des seuils pour "élevé", "moyen" et "faible" ont été définis pour chaque indicateur afin de comparer la capacité de circularité des nutriments (CCN) entre les aires métropolitaines sud-américaines (AMSA), permettant un système de notation simple (faible=0, moyen=1, élevé=2). Un échantillon non exhaustif d'AMSA, couvrant les 10 pays avec de grandes aires métropolitaines selon les critères de l'OCDE, a été sélectionné pour refléter la diversité géographique et la taille de la population.

RÉSULTATS : Douze facteurs influents (FI) ont été identifiés dans quatre thèmes centraux : Potentiel de flux de matériaux, Caractéristiques de la chaîne de valeur alimentaire et animale, Base de connaissances et Soutien institutionnel. Ces FI ont été liés à 33 variables de substitution et 39 indicateurs possibles, qui ont été évalués par une analyse multicritère, aboutissant à trois classements d'indicateurs de circularité des nutriments faisables et représentatifs. Parmi ces classements, 11 indicateurs ont été sélectionnés, couvrant les deux tiers des FI. Ces 11 indicateurs ont ensuite été comparés à 56 indicateurs existants dans des bases de données internationales. Six ont été correctement associés, tandis que les cinq autres, liés à la capacité matérielle locale, ont été reformulés en raison de problèmes d'échelle ou d'informations obsolètes. Après la sélection des indicateurs, les données ont été collectées et traitées pour les aires métropolitaines sud-américaines (AMSA).

Les valeurs des indicateurs révèlent que l'Uruguay avait la capacité organisationnelle la plus élevée parmi les pays sud-américains, grâce à un soutien gouvernemental fort pour l'innovation, la création de connaissances et les politiques d'économie circulaire. Le Paraguay et la Bolivie ont obtenu les scores les plus bas, avec un investissement minimal dans la création de connaissances et aucune politique d'économie circulaire. Santiago, Montevideo et Santa Cruz de la Sierra ont montré les capacités matérielles les plus élevées, tandis qu'Asunción, Sao Paolo et Lima avaient les plus faibles, en raison d'activités agricoles limitées et de systèmes de gestion des déchets insuffisants. Montevideo a obtenu le meilleur score de capacité de circularité des nutriments (CCN) avec 14 points sur 20, tandis qu'Asunción était à

la traîne avec seulement 3 points. Le score moyen de CCN dans toutes les zones était de 9, avec une médiane de 10.

DISCUSSION : Cette évaluation des facteurs influençant la transition vers des systèmes de gestion circulaire des nutriments semble être la première du genre pour l'Amérique du Sud, tant au niveau national qu'à celui des aires métropolitaines. Les études sur les transitions durables et la circularité des nutriments dans la région sont rares, et bien que l'intérêt pour la recherche sur l'économie circulaire soit en croissance, un obstacle majeur à sa mise en œuvre est le manque de consensus sur les principes du concept et son applicabilité (Betancourt Morales et Zartha Sossa 2020). Ces auteurs soulignent également la nécessité d'un cadre conceptuel simplifié qui tienne compte des différences culturelles et économiques entre l'Europe, où le concept est largement étudié, et l'Amérique latine. Cette étude a synthétisé des centaines de facteurs dans un cadre de 4 Thèmes centraux, 12 Facteurs influents et 11 Indicateurs, fournissant un outil pratique pour tout contexte. De plus, ces concepts ont été rendus mesurables grâce à des indicateurs basés sur des données préexistantes, mais sous-utilisées.

La capacité de circularité des nutriments (CCN) variait parmi les aires métropolitaines sud-américaines (AMSA), aucune zone n'étant en tête ou à la traîne dans tous les aspects. Montevideo, en Uruguay, avait la CCN la plus élevée, tandis qu'Asunción, au Paraguay, était la plus basse, bien que la plupart des AMSA aient montré des niveaux globaux similaires. La haute CCN de Montevideo est en corrélation avec son PIB par habitant, ce qui suggère que des facteurs économiques pourraient constituer un obstacle clé pour des pays comme le Paraguay et la Bolivie. Cependant, des économies de niveau intermédiaire comme Bogotá et Quito ont atteint des niveaux de CCN plus élevés grâce à une gestion efficace des déchets organiques. L'agriculture périurbaine, l'investissement dans l'innovation et une gestion environnementale efficace étaient les principaux moteurs d'une CCN plus élevée dans les AMSA.

ARTICLE 2 :

La transition vers une gestion durable des nutriments nécessite un changement systémique et une planification stratégique (Medeiros et van der Zwet, 2020). La planification urbaine stratégique de l'ONU-Habitat met l'accent sur une approche systématique, en priorisant les enjeux clés grâce au consensus et à l'analyse (ONU-Habitat, 2007). Les évaluations initiales sont essentielles pour la formulation de stratégies, en particulier pour aborder les divers facteurs influençant la circularité des nutriments (Arciniegas et al., 2019). Cependant, l'intégration de ces facteurs est difficile, car la métabolisation urbaine et la planification urbaine fonctionnent souvent de manière distincte. Cette séparation prive les institutions des connaissances essentielles pour le développement de politiques globales (Binder, 2007;

Yetano Roche et al., 2014). Cette recherche vise à combler cette lacune en développant un cadre de diagnostic stratégique multidimensionnel, applicable à des contextes réels, pouvant contribuer aux processus de planification urbaine stratégique. Ce cadre a été appliqué à la région métropolitaine de Santiago, un précurseur régional en matière de capacité de circularité des nutriments, pouvant servir d'étude de cas représentative pour les zones urbaines confrontées à des défis similaires (Fleitas Girett et al., 2023).

MÉTHODOLOGIE : Cette recherche suit l'outil "Our City Plans" de l'ONU, en particulier le Bloc D "Analyse et Diagnostic" de la Phase 1 "Évaluation" (Annexe A), afin de s'aligner sur les processus de planification urbaine. Le processus de diagnostic commence par des recherches documentaires et de terrain, suivies d'une analyse et d'une validation. La participation des parties prenantes est essentielle, avec des entretiens semi-structurés réalisés avec des acteurs publics, privés et civils pour la collecte et la validation des données. Les acteurs ont été initialement identifiés à partir de documents de politique nationale ou régionale pertinents, puis élargis en utilisant la méthode de boule de neige au cours des entretiens. Les entretiens ont été réalisés en personne ou via Zoom, enregistrés et transcrits à l'aide d'Amberscript (guides d'entretien en Annexe B).

Le périmètre spatial et temporel du système est défini pour équilibrer exhaustivité, faisabilité et fonctionnalité. Cela implique de revoir les caractéristiques du système agroalimentaire régional et la disponibilité des données, en tenant compte des facteurs institutionnels et en définissant les objectifs stratégiques. Les limites de l'analyse sont fixées pour garantir que l'étude reste alignée sur les objectifs locaux, en identifiant les activités principales au sein des sous-systèmes et les flux de nutriments clés entre eux. Les activités représentant 50 % ou plus du total de chaque sous-système sont prioritaires, avec les flux de nutriments identifiés à partir de la littérature scientifique, de rapports techniques et des données PRTR. Le système est ensuite représenté dans un diagramme montrant les sous-systèmes agroalimentaires et de gestion des déchets, les activités principales et les flux de nutriments clés.

Cette recherche adopte une approche multidimensionnelle basée sur le cadre Ecopolis (Tjallingii, 1995), intégrant les dimensions spatiale, matérielle et sociale. La dimension spatiale traite des activités du système agroalimentaire et de gestion des déchets sur le territoire, la dimension matérielle se concentre sur les flux de nutriments, et la dimension sociale prend en compte les rôles, préoccupations et interactions des acteurs concernés.

Tout d'abord, les données spatiales de base telles que les limites administratives et l'utilisation des terres sont collectées à partir des bases de données locales et traitées à l'aide de logiciels SIG. L'analyse se concentre sur les flux "décourageants" et "opportuns" stratégiquement significatifs, en donnant la priorité aux flux contenant des nutriments dans trois catégories : a) les flux de déchets de tous les sous-systèmes dirigés vers le traitement, la disposition finale ou perdus dans l'environnement ; b) les sorties réutilisées dans la production végétale, animale

ou alimentaire ; et c) les produits d'entrée dans la production végétale et animale. Le contenu en nutriments des matériaux en sortie est regroupé en tissus végétaux, tissus animaux ou boues des stations d'épuration (STEP), avec des niveaux d'azote, de phosphore et de potassium calculés à l'aide de logiciels de tableur, sur la base de la littérature, de rapports techniques et de données locales. En plus des entretiens, les sites officiels des organisations concernées sont examinés pour identifier leurs objectifs, domaines d'intervention et collaborations. Les parties prenantes sont caractérisées par leur lien avec les sous-systèmes agroalimentaires et de gestion des déchets, leurs rôles en tant que parties prenantes (conformément à Bijon et al., 2023), et leurs principales priorités en fonction de leurs objectifs et responsabilités. Pour évaluer les connexions entre les acteurs, une matrice de réseau social est créée (Borgatti et al., 2009 ; Ghinoi et al., 2020), en se concentrant sur la question de savoir si deux acteurs collaborent régulièrement dans la gestion des flux matériels clés, tout en respectant les limites analytiques définies plus tôt dans le diagnostic.

Enfin, deux indicateurs ont été proposés pour intégrer les résultats de l'analyse multidimensionnelle et évaluer les préoccupations clés des stratégies de circularité des nutriments : a) réduire la gestion linéaire des déchets dans les zones urbaines pour minimiser les pertes de ressources et la contamination de l'environnement, et b) augmenter la réintégration des matériaux secondaires dans les processus de production afin de réduire l'extraction des ressources et d'améliorer la sécurité alimentaire régionale.

RÉSULTATS : Le cadre diagnostique a été validé dans la région métropolitaine de Santiago du Chili (RMSC), en se concentrant sur les activités et les flux de nutriments dans ses six provinces et 52 communes. Des données de 2021 ont été utilisées, appuyées par une récente enquête agricole. En plus d'une revue de la littérature, 34 entretiens semi-structurés ont été menés avec des acteurs gouvernementaux, privés, civils et académiques. Un diagramme du système a cartographié les principales activités agroalimentaires et de gestion des déchets ainsi que les flux de nutriments, révélant des activités de consommation centrées sur les zones urbaines, tandis que la production alimentaire et le traitement des déchets se concentraient dans les zones périphériques. La production fruitière, en particulier le raisin de cuve, dominait les terres agricoles (59 %), avec des cultures céréalières et des élevages de porcs et de volailles concentrés dans la province de Melipilla.

L'analyse des flux a quantifié les flux d'azote (N), de phosphore (P) et de potassium (K) dans la région, visualisés à l'aide de diagrammes de Sankey hybrides. Dans la RMSC, la demande en nutriments est principalement assurée par l'urée, qui domine la production agricole, notamment pour les céréales et les légumes, tandis que les arbres fruitiers dépendent fortement des engrais potassiques avec une utilisation limitée de phosphore. Les données sur les bio-intrants tels que le compost sont rares, et l'alimentation animale dépend largement des importations de soja, de maïs et de blé, complétées par certains additifs locaux. Du côté de

l'offre, la production végétale et animale génère des déchets non traités, tandis que la production alimentaire produit des sous-produits bruts et des boues des stations d'épuration (STEP). Les agriculteurs sous-estiment souvent la valeur du fumier, ce qui entraîne une accumulation de nutriments et des pertes environnementales. Les ménages contribuent de manière significative aux pertes de nutriments par le biais de déchets mis en décharge, tandis que les installations de traitement rejettent des matériaux transformés tels que le compost et les boues. La RMSC fonctionne comme un puits de nutriments, la plupart des ressources étant utilisées une seule fois. Les excédents de nutriments diminuent lorsqu'on tient compte des importations d'aliments pour animaux, bien que les excès varient selon les zones, et la pollution par le phosphore dans le fleuve Maipo est probablement liée aux effluents des STEP. Les indicateurs de circularité des nutriments ont fourni une mesure comparative de la récupération des nutriments urbains et de leur réutilisation agricole au niveau régional. Les scores des indicateurs RUN, convertis en pourcentages, ont montré des taux de récupération de 78 % pour l'azote, 85 % pour le phosphore et 52 % pour le potassium, avec un score de récupération combiné de 72 %. Ce score élevé est dû au traitement des eaux usées, la plupart des rejets urbains étant dirigés vers les stations d'épuration. L'amélioration de cet indicateur nécessite une augmentation de la récupération des déchets solides organiques, tels que les déchets alimentaires et de jardin, actuellement envoyés en décharge.

Dans la dimension humaine, 45 acteurs clés ont été identifiés et classés par type de rôle (matériel ou influent) et préoccupation principale. L'analyse a révélé 12 acteurs matériels, 28 acteurs influents et 5 remplissant les deux rôles. En ce qui concerne la récupération et la réutilisation des nutriments, 21 acteurs se concentraient sur la réutilisation des nutriments en agriculture, 16 sur la récupération des nutriments urbains, et 8 sur les deux.

DISCUSSION : La région métropolitaine de Santiago du Chili (RMSC) fait face à des défis importants pour répondre aux besoins en nutriments en raison de sa dépendance aux importations et de son manque de contrôle des nutriments dans les sols. Le diagnostic met en évidence une déconnexion entre les zones rurales et urbaines et entre les secteurs, soulignant la nécessité de stratégies intégrées de gestion des ressources et d'une meilleure collaboration entre les parties prenantes.

Des obstacles tels que la sensibilisation limitée, la méfiance envers les produits recyclés et les barrières réglementaires entravent la récupération des nutriments à partir de sources comme les boues des stations d'épuration (STEP) et les lisiers animaux. L'absence de l'agriculture circulaire dans les programmes universitaires accentue encore l'écart de connaissances, limitant le nombre de professionnels capables de conseiller sur l'utilisation des engrais organiques. Malgré les pertes de nutriments notables, notamment à partir des déchets organiques, l'indicateur RUN montre un potentiel de récupération considérable. En agriculture et en assainissement urbain, les efforts pour minimiser les pertes d'azote réduisent le besoin

d'une gestion active de l'azote. Cependant, les budgets municipaux limités pour la gestion des déchets aggravent les contraintes logistiques et technologiques. La recherche et le développement, concentrés dans le secteur privé, limitent encore l'accessibilité et la diffusion des solutions innovantes.

Cette recherche offre un cadre diagnostique adaptable pour soutenir la circularité des nutriments à l'échelle régionale, aidant les planificateurs locaux à identifier les défis, opportunités et synergies à travers les frontières urbaines-rurales et sectorielles. En se concentrant sur les activités principales et les flux de nutriments, le diagnostic simplifie l'interprétation et fournit des informations pratiques et spécifiques au contexte. La cartographie de la répartition spatiale des activités aide à visualiser les flux de nutriments et à identifier les opportunités de collaboration et de planification des infrastructures. L'analyse des flux clarifie comment l'azote, le phosphore et le potassium (NPK) sont demandés, perdus ou récupérés, permettant des stratégies ciblées pour réduire les pertes et augmenter la récupération, améliorant ainsi l'autosuffisance et la sécurité alimentaire. De plus, le cadre permet d'identifier les acteurs clés pour leur inclusion dans les stratégies de circularité des nutriments et renforce les liens entre les parties prenantes alignées.

ARTICLE 3

Dans ce travail, nous allons un pas plus loin en cherchant à combler l'écart entre un diagnostic territorial des flux de nutriments et la construction de scénarios grâce au développement de récits. Nous proposons un cadre qui intègre les résultats du diagnostic avec les apports des parties prenantes et les stratégies locales pour construire ces récits, offrant une perspective de circularité des nutriments fondée sur des preuves et contextualisée pour les processus de construction de scénarios actuels et futurs, ainsi que pour les exercices d'exploration de visions dans le cadre du développement urbain circulaire. Comme pour le cadre de diagnostic précédent, nous avons appliqué ces outils à la région métropolitaine de Santiago, un leader régional en matière de capacité de circularité des nutriments.

MÉTHODOLOGIE : Le cadre proposé dans cette étude vise à relier l'étape d'analyse et de diagnostic à l'étape de construction de scénarios par le biais de récits, en s'appuyant sur le cadre "Our City Plans" proposé par l'ONU-Habitat (2022) et sur l'approche SAS proposée par Alcamo (2005). Le développement des récits scénaristiques se compose de trois tâches principales : la contextualisation des données, la synthèse des résultats et la construction des récits eux-mêmes. Les première et deuxième tâches consistent à rassembler et à catégoriser les informations relatives à la gestion des flux contenant des nutriments à partir de trois sources : le diagnostic stratégique multidimensionnel, les principaux documents de politique publique et les apports des parties prenantes. Cette tâche implique le développement de

questions focales, la collecte des retours des parties prenantes, et enfin, l'identification et la connexion des éléments narratifs.

RÉSULTATS : L'examen des politiques a identifié deux objectifs globaux liés aux flux contenant des nutriments : 1) augmenter le recyclage des déchets organiques municipaux et 2) promouvoir une production agricole durable. Les points de vue des parties prenantes concernant les objectifs, les obstacles, les stratégies et les priorités ont été organisés, mettant en évidence des défis clés. En termes de potentiel de flux de matériaux, une infrastructure de traitement des déchets insuffisante, des coûts de transport élevés et des restrictions réglementaires ont été notés comme des obstacles majeurs. Les défis de la chaîne de valeur incluaient un manque de sensibilisation, de confiance dans les matériaux secondaires et de collaboration entre les secteurs, ainsi que des limitations financières et techniques. La base de connaissances locales était entravée par un manque de recherche indépendante, de formation sur les pratiques circulaires et par l'influence des entreprises d'engrais minéraux. Les défis institutionnels comprenaient des règlements obsolètes, des protocoles de gestion des déchets insuffisants et une répartition inégale des ressources entre les municipalités.

Les variables ont été identifiées à partir des documents de politique publique, des apports des parties prenantes et du cadre de diagnostic, puis catégorisées par sous-système, facteur d'influence et objectifs de circularité des nutriments (CN). Les chevauchements et lacunes dans les défis, opportunités et stratégies ont été liés à des secteurs ou intérêts partagés pour former des propositions stratégiques. Trois questions focales ont été développées pour explorer des solutions potentielles :

- Et si la capacité de compostage était augmentée et que les espaces verts urbains étaient maintenus grâce aux nutriments récupérés à partir des déchets municipaux ?
- Et si les nutriments des résidus animaux étaient utilisés plus efficacement et appliqués à davantage de cultures ?
- Et si les technologies des STEP étaient améliorées, permettant d'appliquer les nutriments des boues aux cultures telles que les fruits et légumes ?

Ces questions ont été présentées aux parties prenantes lors d'un atelier à Santiago, au Chili, où des retours ont été collectés. Les deux premières questions traitaient des objectifs partagés dans l'examen des politiques, tandis que la troisième dépassait les politiques actuelles, intégrant une vision systémique fondée sur les résultats du diagnostic. Les récits qui en ont résulté ont comblé les écarts entre les sous-systèmes et les facteurs d'influence, en abordant des domaines qui ne sont pas encore prioritaires dans les plans existants.

DISCUSSION : Le cadre proposé relie la phase d'évaluation à la phase de planification, offrant un modèle rigoureux que d'autres villes et organismes de planification peuvent adopter pour améliorer leurs processus. Il favorise une perspective systémique essentielle à la circularité des nutriments, encourageant les acteurs à explorer des stratégies alternatives qui vont au-

delà des pratiques actuelles. En offrant une vue d'ensemble, le cadre soutient une prise de décision éclairée et renforce l'engagement des parties prenantes (Alcamo et al., 2005 ; Mallampalli et al., 2016). En ancrant les récits dans une analyse multidimensionnelle, les apports des parties prenantes et les principes fondamentaux de la circularité des nutriments, ce cadre évite les solutions incomplètes, favorisant des transformations systémiques plus larges. Cette approche permet de développer des stratégies intégrées pour la gestion des flux contenant des nutriments, essentielles à la durabilité urbaine et régionale. Dans des villes comme la région métropolitaine de Santiago du Chili (RMSC), où la planification circulaire est déjà en cours, ces résultats peuvent aider à évaluer et à adapter les plans existants, en proposant des alternatives visant une circularité systémique plus profonde.

In conclusion, this research presents a robust framework for advancing nutrient circularity in South America by systemically analyzing nutrient flows to enhance strategic planning. It begins by establishing a clear understanding of nutrient circularity and developing a method to measure it at a territorial level, offering valuable insights into the factors that shape nutrient flow management. Building on this foundation, the framework guides the execution of a comprehensive, multidimensional diagnostic that remains strategic, balancing detailed analysis with practical applicability. This diagnostic is then synthesized with local goals and concerns to construct actionable narratives that inform future planning processes. By addressing the core factors influencing nutrient flows, the study provides a structured, comprehensive approach to assessment, as well as facilitating the translation of findings into strategic insights for decision-makers and planners through strategic planning processes.

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1. INTRODUCTION

Cities and metropolitan areas are key to advancing sustainable development, a foundational principle of both urban metabolism and urban planning. Despite the potential synergy between these disciplines, their integration in real-world urban development processes remains challenging. This is particularly evident in the management of nutrient-containing materials such as fertilizers, food products, and organic waste. As cities grow and strive to improve their sustainability and resilience—especially in the face of climate change—their approaches to managing these agrifood systems or “biological” flows are often fragmented and inadequate. This situation prompts the critical question: How can nutrient circularity be effectively and systemically incorporated into the design of sustainable urban development strategies?

This research aims to systematically and systemically analyze nutrient flows to enhance strategic planning processes towards increased nutrient circularity. The study’s area of focus is South America due to its global significance in agrifood production and rapid urbanization. Before discussing the detailed research processes and findings of the three aforementioned steps, the main theories and frameworks underpinning the study are introduced, with further exploration and specificity of literature provided in the subsequent chapters.

1.1. Cities, Regions, Territories

One of the most significant transformations in recent decades has been the global shift from predominantly rural to urban living. The World Bank (2018) projects that over two-thirds of the world’s population will reside in cities by 2050. Although the definition of a city or urban area varies across sources, it is generally associated with administrative boundaries, population density, and built-up areas. While urban areas tend to foster higher levels of innovation and provide better access to public services, they are frequently accompanied by substantial social inequality and environmental degradation (OECD 2020). The activities that take place within the administrative limits of large cities often extend into neighboring smaller towns and cities, creating a continuous exchange of people and resources, which collectively form a "metropolitan area" (Da Cruz et al. 2020). The term "region" can also overlap with "metropolitan area" but generally refers to a broader territory encompassing multiple cities and diverse land uses, both urban and non-urban (Gleeson and Spiller 2012).

These complex territorial configurations concentrate resources critical for socio-economic transitions, including human capital, research institutions, economic activity, and institutional engagement, while often containing the spatial diversity needed for resource revalorization (Modrego and Berdegué 2015). Metropolitan areas and similar territorial scales enable the integration of top-down strategic planning with varying degrees of participatory governance and co-creation processes (Medeiros and van der Zwet 2020).

Urbanization is characterized by the growth of city populations and the expansion of land use for urban purposes, often manifested through urban sprawl, which involves the replacement of natural landscapes with built environments (Deng et al. 2024; Wang et al. 2020). This process is typically driven by rapid population growth and shifts in urban spatial patterns, leading to urban expansion that is associated with various negative impacts, including increased traffic congestion, loss of productive land, and heightened social segregation (Rojas et al. 2013).

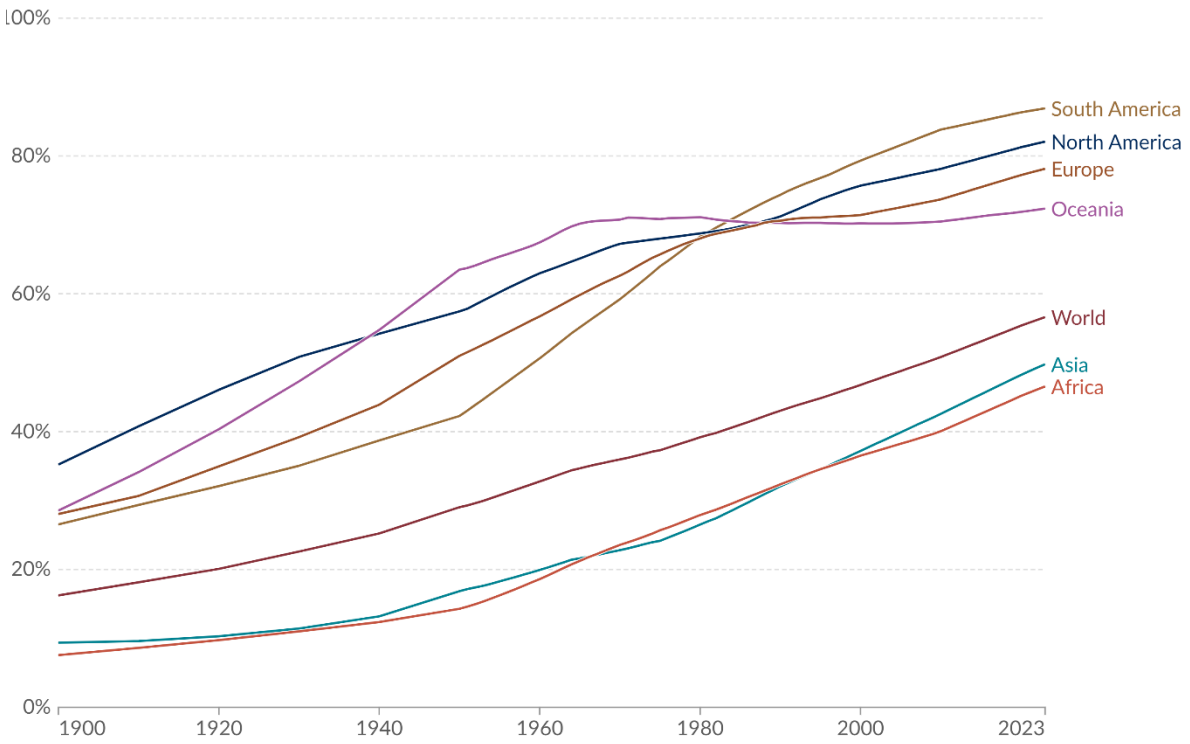

Figure 1. Share of population living in urbanized areas (1900 to 2023). Source: (HYDE 2023).

According to the United Nations Population Division (2018), the most urbanized regions globally are Northern America (82%), Latin America and the Caribbean (81%), and Europe (74%) (see Figure 1). In Latin America, urban areas are expanding at an average rate of 20 m² per minute, much of which occurs through informal and unregulated development, often referred to as "new urban peripheries" (NUPs) (Inostroza 2017). This phenomenon is also known as residential segregation, whereby groups with similar characteristics are concentrated in specific areas of a city, often influenced by public sector policies (Borsdorf et al. 2016). These areas frequently lack essential public services, such as waste collection, and are subject to weak urban regulation from public institutions (Canese de Estigarribia, M. I. et al. 2019). Another common issue is environmental inequality, defined as the uneven distribution of environmental goods, services, risks, and hazards, often along lines of race and income (Smets and Salman 2016).

1.2. Sustainable Urban Development, in Theory

The concept of "sustainable urban development" (SUD) began gaining prominence in the 1990s, first introduced by Elkin et al. (1991) and later reinforced by major international conferences of the decade, such as the UN Rio Earth Summit and the Habitat Conference. These events underscored the critical role cities play in addressing global environmental challenges. Despite its growing popularity, the SUD concept has historically been challenging to define in concise terms (Cooper 2017). After an extensive literature review, Wheeler (1996) proposed that "sustainable urban development seeks to create cities and towns that improve the long-term health of the planet's human and ecological systems."

Traditionally, urban development has been characterized by socio-spatial processes that externalize both the input of resources and the output of waste flows (Esculier et al. 2019). In many cities, the model of resource consumption follows a linear and open system, where resources are imported, processed, consumed, and then discarded. While some waste is treated and recovered, a significant portion is released back into the environment, exacerbating ecological strain.

Cities consume over 75% of the world's resources and produce around 50% of global waste (Lucertini and Musco 2020). These vast material exchanges extend beyond city boundaries, as most goods are produced and processed externally, while waste is often managed in outlying areas. This consumption model has significant environmental impacts, including resource depletion, increased energy use, and contamination (Kraker et al. 2019). This externalization increasingly poses risks to a city's sustainability and resilience, especially in light of climate change and potential political or economic crises.

Nutrient-containing flows—those involving nitrogen, phosphorus, potassium, and organic matter—form a crucial subset of these externalized flows, contributing both to resource input and waste output. In recent years, there has been a heightened focus among scientists and policymakers on agricultural and human nutrition systems due to their significance for both human survival and environmental sustainability. These studies have highlighted the challenges of achieving global food security and have proposed alternatives, including changes in diets, the redesign of production systems, adjustments in trade policies, and a reduction in food waste (Billen et al. 2021).

1.2.1. Urban Flows

Tjallingii (1996) argued that the openness of territorial systems—characterized by increased resource inflows and outflows—jeopardizes spatial diversity and leads to "source and sink"

problems, such as resource depletion and contamination. These findings align with later research on urban metabolism (UM) and circularity, which gained recognition for addressing similar issues (Lucertini and Musco 2020). Urban metabolism (UM) is defined as the study of "the sum of technical and socioeconomic processes within cities," analyzing the movement of resources, including inflows, outflows, and accumulation within a specific territory (Kennedy et al. 2011).

Its growing popularity stems from its ability to integrate multiple disciplines like industrial economy, urban ecology, and political ecology, all of which are essential for sustainable urban development (Perrotti 2020). Urban metabolism (UM) research explores how material flows are interconnected with broader socio-economic systems, often extending beyond the administrative boundaries of cities or regions. This concept integrates theories from industrial ecology, systems thinking, and environmental economics, offering a comprehensive approach to sustainably managing material flows within urban environments. Building on these principles, circular urban metabolism focuses on reducing resource inputs, recirculating waste, and valorizing waste streams to minimize environmental impacts (Peng and Pivato 2019).

Oliveira and Vaz (2021)identified three key areas of focus within UM studies: theory, quantification (also known as accounting), and application. In addition, UM have been conducted at various scales—from city to territorial levels—and have addressed multiple or specific urban metabolic components (Beloin-Saint-Pierre et al. 2017). Despite having similar objectives, these assessments employ a range of methodologies, from addressing specific issues to adopting more systemic approaches. Among the most widely used UM accounting methodologies are Material Flow Analysis (MFA), energy assessments, input/output analyses, ecological footprint calculations, and life cycle assessments (Allesch and Brunner 2015). MFA, a flexible and adaptable method, is commonly applied for modeling mass balances of materials and energy within a territory (Hoekman and Bellstedt 2020). To better visualize these complex flows, researchers frequently use Sankey diagrams, which represent flows within a defined functional unit or time period. The width of the flow lines in these diagrams indicates the magnitude of the flows (Lupton and Allwood 2017).

Within UM accounting methods, common approaches include territorial, supply chain, and consumption-based frameworks. Territorial approaches focus on resources within a geographic boundary, supply chain approaches address cross-boundary resource flows, and consumption-based methods assess the impacts of final consumed products (Yetano Roche et al. 2014). Territorial and supply-chain approaches are particularly recommended for

informing local and regional infrastructure planning as they provide valuable insight into local production and infrastructure characteristics (Yetano Roche et al. 2014).

Considering its multidisciplinary and systemic nature, UM research has the potential to provide critical insights for urban policy and strategic development by identifying links between material flows and socio-economic systems, suggesting infrastructure redesign, and exploring resource recovery opportunities (Lucertini and Musco 2020)." Nonetheless, despite its valuable contributions, UM has been criticized for its "black box" nature, which can obscure the complex spatial, environmental, and socio-economic impacts of resource flows (Beloin-Saint-Pierre et al. 2017; Hoekman and Bellstedt 2020; Perrotti 2020). To address these limitations, recent efforts have focused on integrating flow processes with network models, enabling a more detailed analysis of internal mechanisms and interactions between subsystems (Zhang et al. 2015). Moreover, UM research has progressed beyond diagnostic methods, increasingly incorporating planning tools such as scenario modeling and simulations to generate quantitative insights (Billen et al. 2018; Tsui et al. 2022). These integrated approaches are further discussed in Section 1.2.3.

1.2.2. Urban Planning

In addition to managing the quantity and quality of resource flows, sustainable urban development requires a spatial understanding of where resources are located and how they move within the system (Lucertini and Musco 2020). Although the spatial characteristics associated with sustainable development remain a topic of debate, there is general consensus that spatial variation—referring to the diverse land uses and activities within a territory—plays a crucial role in stabilizing urban systems (Cumming 2011).

Urban planning frameworks and tools aim to shape the planning, design, and development of cities and regions to tackle inequality, promote sustainability, build resilience, and improve overall quality of life (United Nations 2017). As a fundamentally interdisciplinary field, urban planning strives to achieve integrated urban development by fostering collaboration between different levels of governance and across various sectors (Ferry et al. 2018). This collaborative approach is essential for effective planning, as it involves working across multiple territorial scales and engaging a diverse range of stakeholders (Medeiros and van der Zwet 2020).

Strategic urban planning addresses three core questions: (1) Where are we now? (2) Where do we want to go? and (3) How do we get there? (UN Habitat 2007). The initial question requires a comprehensive urban diagnosis that examines the existing physical, environmental, and socio-economic conditions of the area, along with the identification of relevant

stakeholders. This diagnostic phase often involves spatial analysis, facilitated by geographic information systems (GIS), to evaluate spatial trends and inform strategy development, ensuring coordination between various territorial and sectoral entities (Ek and Santamaria 2009). Additionally, local stakeholder engagement through methods such as interviews, surveys, and workshops play a vital role in enhancing the depth and inclusivity of the planning process (Cabannes, Y., Marocchino, C. 2018). Successfully completing this initial assessment phase is crucial before advancing to the planning and implementation stages. However, in both research and real-world planning processes, questions remain about how to effectively implement such a comprehensive assessment, particularly for nutrient-containing flows, and even more crucially, how to effectively connect these stages.

1.2.3. Multi-, Inter-, & Transdisciplinary Work

Sustainable development has traditionally been framed around three core dimensions: social, environmental, and economic. However, in practice, sustainability is understood as a complex interplay of factors and processes that requires a multidisciplinary approach, integrating these dimensions from the outset. Challenges often arise when research or planning begins with a focus on one dimension and later attempts to incorporate the others during implementation, rather than conceptualizing them with integration in mind from the beginning (GIBSON 2006).

The transition to more sustainable economic systems necessitates the simultaneous consideration of social, environmental, and economic aspects, while also taking into account local actors and values. Numerous studies emphasize the importance of this multi-dimensional approach for achieving a comprehensive understanding of sustainable transitions (Harder et al. 2021; Poponi et al. 2022; Petit-Boix and Leipold 2018; Gottinger et al. 2020). Moreover, the integration of diverse perspectives is crucial in developing circular economic and resource management systems, which are increasingly recognized as vital components of sustainability (Iacovidou et al. 2020).

Efforts to study and design sustainable urban and regional plans consistently emphasize the importance of adopting transdisciplinary perspectives and approaches in order to develop comprehensive proposals. However, achieving this integration can be challenging, often resulting in the prioritization of one discipline over another, typically aligned with the researcher’s own background and training. Müller et al. (2005) propose a Transdisciplinary Learning Model that addresses this issue by considering basic learning cycles, wherein exchanges between the internal world (thoughts, knowledge, ideas, values, norms) and the external (physical) world occur through three key steps: normative, creative, and descriptive. They argue that the most effective way to support transdisciplinary research is not by fully

integrating other disciplines as research activities—since these disciplines often have different goals—but by incorporating relevant aspects of other fields while maintaining the primary focus of one's own discipline.

An example of a transdisciplinary approach to sustainable urban development is the "Ecopolis Strategy Framework" for "ecologically sound development," which focuses on three key areas: areas, flows, and actors (Tjallingii 1996). Initially developed from a planning perspective, this framework was later expanded in Tjallingii's subsequent work, where he rebranded it as the "Ecological Conditions Strategy." This strategy serves as a planning tool for sustainable development, emphasizing the need for responsible flows, well-managed living areas, and active participation from relevant actors. Building on this foundation, Tsui et al. (2022) further refined the framework, referring to the key areas as flows, space, and people. In this iteration, the role of each focus area is elaborated: the spatial perspective explores how land use, planning, and zoning strategies impact circular activity and material flows within regions; the flow perspective aligns with urban metabolism studies that analyze resource flows; and the people perspective emphasizes urban governance and decision-making. Ultimately, Tjallingii's framework moves beyond the traditional three pillars of sustainability by embedding these core concepts within urban planning. It incorporates essential spatial elements that decision-makers and urban planners require to effectively operationalize and implement sustainability projects (Loiseau et al. 2012; Yetano Roche et al. 2014).

Loiseau et al. (2012) argued that urban metabolism tools and methods "should provide stakeholders with useful information to assist them in the development of public policies and decision-making, particularly for territorial planning." But once again we must ask, how is this practically done? Tjllingii and Tsui et al.'s flows-people-space framework offers a key step towards connecting urban planning and urban metabolism principles and tools by identifying the types of data and analyses that should be included in urban assessment and planning processes. In addition, Oliveira and Vaz (2021) proposed several key principles for more urban metabolism research in terms of research designs that are aligned with planning needs and functions:

a) Inputs from research must be tailored to the specific requirements of practical application.
b) Urban metabolism should be evaluated within the context of planning practice.
c) Different metabolic components should be assessed at varying scales.
d) The measurement of metabolic components should balance research complexity with practical pragmatism.

e) The significance of land as a resource should be reinforced within the metabolic framework and acknowledged as a key factor in linking research to practice.

Despite their importance, many existing UM studies overlook or neglect these principles. For instance, research inputs are often highly theoretical, relying on estimates from abstract calculations, and without being tailored to the specific characteristics of a city or metropolitan area, limiting their practical applicability. Moreover, UM research is frequently conducted in isolation from actual planning processes, disregarding the strategies and policies that practitioners are currently focused on. Additionally, UM studies often analyze material flows at either a highly detailed level—such as industrial ecology between specific industries or sectors—or at a highly generalized macro level encompassing entire cities. While these assessments are valuable, urban metabolism research for planning must integrate different scales in a strategic way that still avoids unnecessary complexity and remains accessible for practical use. Finally, land use and territorial planning, despite being inherently connected to territorial flow accounting, are often inadequately addressed or overlooked in existing research.

Recent urban metabolism studies have attempted to become more comprehensive and planning-oriented. This includes incorporating non-accounting methodologies such as agent-based modeling, scenario analysis, and typology development (Hoekman and Bellstedt, 2020). Practical frameworks have also been developed through European regional planning projects, including the Rural Urban Nexus project by the German Federal Environmental Agency (Burger and Kuhn 2018) and the REPAiR (REsource Management in Peri-urban Areas) EU Horizon 2020 project (Taelman et al. 2018), both of which engaged stakeholders through workshops. Notable examples in terms of nutrient containing flows include the "multi-pillar mapping" framework proposed by Viva et al. (2020), which integrates Material Flow Analysis (MFA), Sankey diagrams, Geographic Information Systems (GIS) mapping, and social analysis to develop circular and systemic waste management strategies. Similarly, the REPAiR project (Geldermans et al. 2019) introduced an innovative Activity-based Spatial MFA that links material flows with economic activities and relevant actors. For nutrient-containing flows, Jedelhauser and Binder (2018) highlight the importance of spatial analysis at different scales, distinguishing between local assessments for households, regional scales for agriculture, and national or international evaluations for the fertilizer industry. Studies by Papangelou and Mathijs (2021) and Harder et al. (2021) also prioritize regional analyses, connecting nutrient flows to agrifood systems and circularity indicators.

Though urban metabolism methodologies continue to evolve and improve, they remain heavily reliant on analyses and models that, due to their complexity and scope, are often challenging

to integrate into planning processes (Perrotti, 2020; Oliveira and Vaz, 2021). This issue is particularly evident in studies of nutrient-containing flows, which frequently result in descriptive and theoretical insights without the strategic focus or contextual relevance required for practical application in planning. Additionally, neglecting the social, political, and economic factors that influence these flows further hampers the translation of research findings into actionable policies and strategies (Yetano Roche et al., 2014). These challenges make it difficult to effectively incorporate urban metabolism outputs into real-world practice.

1.3. Sustainable Urban Development, in Practice

In response to the challenges posed by climate change and urbanization, cities and metropolitan areas worldwide are actively incorporating sustainability principles into their urban planning processes (Domenech and Borrion 2022). Many countries have committed to the United Nations' Sustainable Development Goals (SDGs) and, in recent years, have been integrating these goals into national and regional development plans (Chimhowu et al. 2019). As part of this commitment, cities and regions globally are developing strategic visions and roadmaps that focus on the sustainable use of resources. These efforts often incorporate popular agendas such as the circular economy and bioeconomy, particularly in response to SDG 11 ('Sustainable Cities and Communities') and SDG 12 ('Responsible Consumption and Production'), both of which emphasize the sustainable management of material flows within territories (Ellen Macarthur Foundation 2019).

One key tool developed to promote sustainable urban development is the United Nations' *Our City Plans Toolbox*, which guides urban planners and stakeholders through the analysis, planning, and implementation of sustainable strategies (UN Habitat 2022). The toolbox provides practical guidance for integrating sustainability into urban projects by addressing economic, environmental, and social dimensions. However, while its generalized and highly adaptable model enhances usability, it also requires supplementary, detailed guidelines to effectively address specific urban sustainability challenges, such as circular nutrient-flow management.

In terms of sustainable resource management, two key international frameworks for development are the bioeconomy and circular economy models. Both of these models aim to replace the current linear economy system. The bioeconomy model, for its part, aims to sustainably produce goods and services based on biological and natural resources, employing biotechnology to decarbonize the economy (Hodson de Jaramillo et al. 2019). Meanwhile, the circular economy focuses on minimizing resource demand and waste through product design, process engineering, and other strategies, while closing resource loops by recycling and

reusing secondary materials (Childers et al. 2011; Stegmann et al. 2020; Valve et al. 2020; Vanhamäki et al. 2020). In the context of the agrifood system, this is often referred to as nutrient circularity or closing nutrient cycles (van der Wiel et al. 2019a).

As cities grow and urbanize, the volume and complexity of waste increases, placing additional strain on waste management systems, particularly in low- and middle-income countries. Cities worldwide are eager to aspire to and adopt resource circularity approaches and plans. Dozens of countries have begun promoting Circular Economy principles through policies and practices, although with varying goals and interests (Zeller et al. 2020). Europe, in particular, has been a leader in this movement, with initiatives such as the European Commission's Circular Economy Package, London's Circular Roadmap, and the Circular City white paper for Paris (Prendeville et al. 2018). Figure 2 confirms the concentration of CE strategies occurring in Europe, where most are either at a roadmap or operational strategy level, while such publications are still rare. Moreover, Chile and Colombia are the only South American countries with a sustainable consumption and production strategy, as well as quantitative targets of CE strategies (UNIDO / Chatham House 2024).

The development and implementation of circular economy practices vary significantly from country to country. One reason for this is the lack of clearly defined extended producer responsibilities and obligations (Besen and Fracalanza 2016). Other barriers include regulatory challenges, limited market access, gaps in science, technology, innovation, and human resources, inadequate funding, and insufficient knowledge (Marin and Meulder 2018). Additionally, current economic systems and sectoral thinking often fail to recognize the value of these waste streams, resulting in a lack of support for symbiotic initiatives (Garreton 2017).

While high-income nations are focused on making waste management more circular, many South American countries continue to face basic challenges in waste collection and disposal (Jaitman 2015). In South America, resource recovery efforts are primarily concentrated on waste flows, but the lack of selective waste collection and management presents a major obstacle to implementing alternative schemes (Besen and Fracalanza 2016). Most resource recovery is carried out by an underappreciated informal sector that works in precarious conditions, manually sorting recyclable materials from open landfills and street bins (Poletto et al. 2016). Experts agree that any alternative waste management strategy must begin by including this sector (Valenzuela-Levi 2019b).

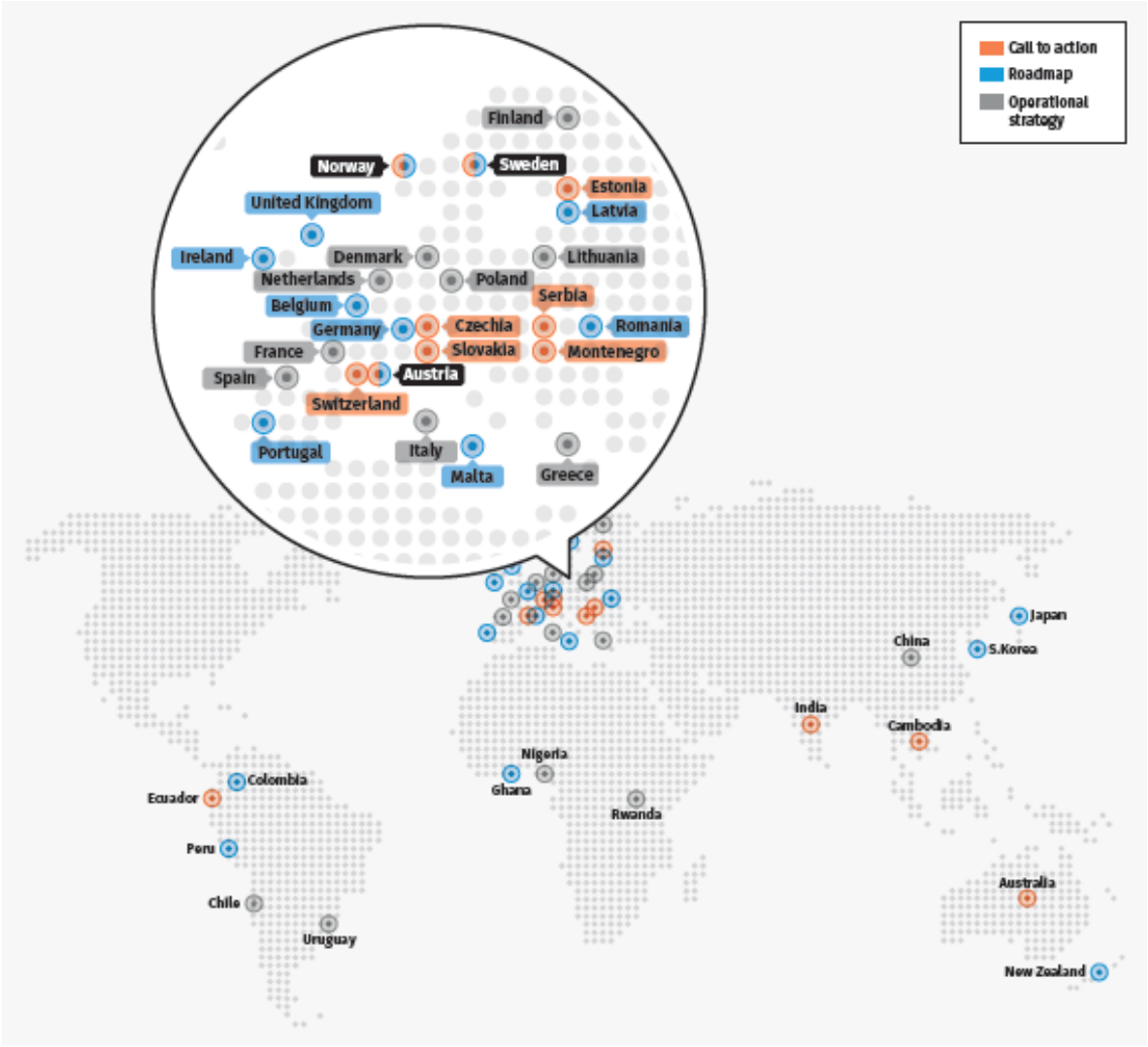

Figure 2. Overview of "Calls to Action", Roadmaps, and Operational Strategies across the world, from UNIDO 2024.

1.4. The gap between research and practice

Petit-Boix and Leipold (2018) highlight a significant gap between research and practice in circular resource management, noting that while cities focus on waste collection systems, much research centers on treatment impacts. Circular economy strategies have also faced criticism for prioritizing resource efficiency over environmental preservation, relying on techno-centric approaches, and neglecting social dimensions (Prendeville et al. 2018). Another challenge is the lack of standardization in monitoring and reporting, leading organizations to use inconsistent indicators that align with individual goals rather than systemic sustainability and circularity (Pauliuk 2018). Additionally, research gaps persist in areas like social consumption, urban planning, and IT-related initiatives, with insufficient integration of environmental performance assessments in circular urban planning. Prendeville et al. (2018) further emphasize the scientific community's responsibility to provide clear guidelines for implementing circular economy concepts.

Moreover, theories and models developed in contexts like the European Union often face difficulties when adapted to regions with different conditions, such as South American metropolitan areas (SAMAs) (Tura et al. 2019). This makes it challenging for decision-makers to determine which factors are most relevant for their specific contexts (Ddiba et al. 2021; Queste and Wassenaar 2019). Furthermore, many studies rely on reference values to estimate flow characteristics, such as agricultural nutrient demand and waste generation rates. Although scientifically sound, these findings can seem too theoretical or abstract for local actors to apply in policy development and implementation (Harder et al. 2021).

1.5. Nutrient Circularity

After decades of linear, intensive agrifood production and consumption systems, countries worldwide are increasingly recognizing the need for circular models of biological resource management (Billen et al. 2021). Urban agglomerations, characterized by high population densities and commercial activities, rely heavily on food imports while generating substantial emissions, particularly from food and sanitary waste. These waste materials are often treated and deposited within the same metropolitan area, forming "nutrient sinks" that play a crucial role in regional nutrient cycles (Kraker et al. 2019; Velenturf and Purnell 2017; Wang et al. 2021; Wielemaker et al. 2019).

As food demand rises, alongside the volatility of chemical fertilizer costs and the negative externalities of landfills, governments face growing pressure to implement policies that reduce nutrient loss and promote the recovery of nutrient-rich materials from waste streams for productive use (Drechsel and Kunze 2001). This shift toward circular management—referred to as closing nutrient cycles or enhancing nutrient circularity—requires not only the recycling of organic waste but also reducing waste generation and integrating bio-based value chains to support a circular economy (Annevelink et al. 2017).

The Ellen MacArthur Foundation’s Circular Economy framework establishes a hierarchy for materials in the “biological cycle,” recognizing that not all recovery schemes offer equal benefits. Strategies to reduce losses and enhance recovery are often guided by the waste hierarchy and the biomass cascade (value pyramid). The waste hierarchy prioritizes preventing and reducing waste, followed by reuse, recycling, recovery, and disposal as a last resort (European Commission 2008). The biomass value pyramid ranks products from nutrient-containing waste, with the highest value in pharmaceuticals, followed by food, feed, bioplastics, chemicals, biofuels, and the lowest in energy products like biobased electricity and heat (Odegard et al. 2012; Werkgroep Businessplan Biobased Economy 2011).

The benefits of increasing nutrient circularity are significant, including enhanced self-sufficiency and security for local food production, reduced environmental contamination from emissions, and the conservation of natural resources such as soil and mineral reserves (van der Wiel et al. 2019b; Borrello et al. 2016). While these advantages are driving global efforts to explore and implement transition strategies, the potential negative impacts of nutrient circularity must also be considered. Sanitary and health risks may arise from the reincorporation and circulation of biological materials from waste streams, including the potential for pathogen exposure in food production systems or the accumulation of heavy metals from soil treatments (Aleisa et al. 2021; Vågsholm et al. 2020). Additionally, strategies must address emissions linked to waste disposal and energy production, along with common economic and logistical challenges, such as transporting liquid waste and the timing of nutrient capture and application (Borrello et al. 2016).

1.5.1. Research

It is important to note that the term 'food systems' is often focused on food production and consumption, though waste flows are also occasionally considered, and the activities and outcomes related to waste treatment and recycling are typically overlooked or considered separately, particularly in the context of planning and policy (Esposito et al. 2020). In contrast, nutrient circularity research encompasses food production, consumption, and waste treatment activities within defined system boundaries, which vary in geographic and material scope (Harder et al., 2021a; van der Wiel et al., 2019). Van der Wiel et al. (2019) uses the term 'agro-food-waste system' and identifies five key subsystems within it: crop production, animal production, food and feed processing, consumption, and waste management (Figure 3).

Van der Wiel et al. (2019) reviewed studies related to nutrient circularity and identified several key trends that align with general patterns observed in most urban metabolism (UM) material flow assessments. These include a focus on areas with nutrient surpluses, the use of administrative boundaries, an emphasis on phosphorus and nitrogen flows, the analysis of static one-year periods, and the predominant use of Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) methods. Recent years have seen extensive exploration of nutrient resource circularity, with scientists developing frameworks to assess nutrient circularity components, particularly focusing on nutrient recovery from urban sanitation flows (Billen et al., 2021; Koppelmäki et al., 2021; Papangelou & Mathijs, 2021; Kraker et al., 2019; Trimmer et al., 2019; Wielemaker et al., 2020). Additionally, social and economic factors influencing agro-food-waste systems were examined by Bijon et al. (2023)offering a classification of the actor roles within them.

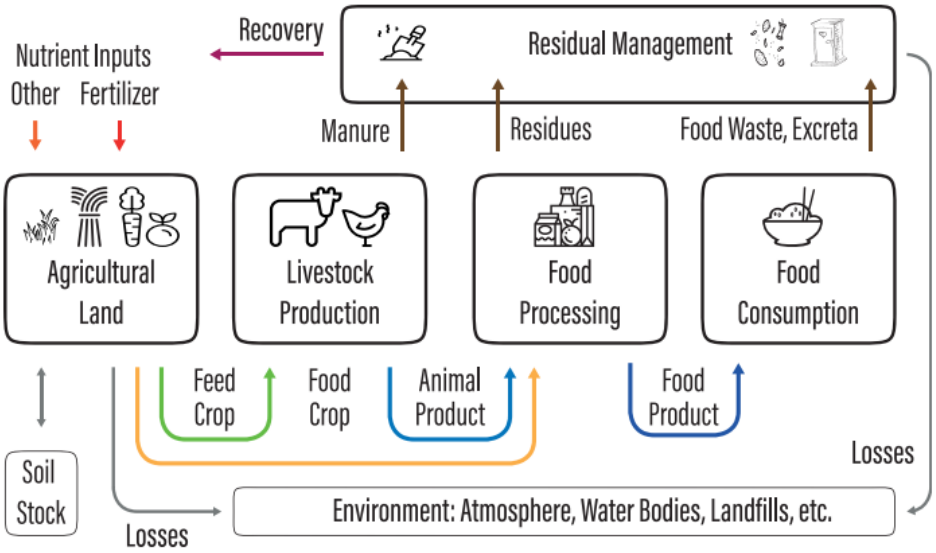

Figure 3. Subsystems and their relationships. From (Harder et al. 2021)

Existing research on agri-food systems has highlighted several key challenges to achieving food security, while also offering potential solutions. These include dietary shifts, redesigning production systems, adjusting trade policies, and reducing waste (Billen et al., 2018). Billen et al. (2018) discuss two contrasting future paths for the French agri-food system: one promotes international agricultural trade with economies of scale, while the other focuses on regionalizing agricultural and nutritional flows to create closed nutrient cycles. The study acknowledges that full self-sufficiency for every world region is unrealistic, and some openness in local economies is inevitable. Additionally, studies suggest that scaling up resource recovery technologies can contribute to zero-waste goals, even in low- and middle-income countries (Swart and Groot 2015). For example, nutrient recovery from urban solid waste and wastewater presents an opportunity to close local nutrient cycles through urban agriculture, though it is often noted that urban nutrient outputs exceed local demand (Wielemaker et al., 2019). Meanwhile, other authors have noted that increasing recycling rates alone will not suffice to meet the growing pressures on waste management systems, and it is essential to consider the co-benefits of resource treatment and recovery (Chen et al. 2020).

Research on regional nutrient balances and hotspot matching has been explored in several studies (Billen et al., 2021; Koppelmaki et al., 2021; Timmer & Guest, 2018; Veldhuis & Yang, 2017; Wielemaker, 2020), though many do not adopt a multi-dimensional perspective, instead usually focusing mostly on material flow related factors. Furthermore, studies have examined the reintegration of urban flows into surrounding rural areas (Wang et al., 2021; van der Wiel et al., 2019; Wassenaar et al., 2014), focusing primarily on technical and material flow aspects (Vayssières and Rufino 2012; Rosemarin et al. 2020) and are often limited to European

contexts (Do et al. 2021; Gottinger et al. 2020). Examples of planning-oriented research include the works of Wielemaker (2019), the REPAiR Project (2018), and Arciniegas et al. (2019), which integrated multiple dimensions of data, such as GIS data, to provide a more comprehensive analysis.

Overall, studies on nutrient circularity at a territorial level are limited in comparison to other urban resources, and research has indicated that while interest in circular economy practices is growing around the world, a key barrier to implementation is the lack of consensus on the principles and applicability of the concept of “circularity” (Betancourt Morales and Zartha Sossa 2020). These authors also emphasize the need for a simplified conceptual framework that can be easily adopted by a variety of local stakeholders, while accounting for the cultural and economic differences between Europe (where the concept has been extensively studied) and Latin America.

1.5.2. Implementation

When adapting nutrient circularity concepts into political agendas, governments have taken varied approaches. Some view it as part of the transition to a Circular Economy or Bioeconomy, while others have combined them with terms like "Circular Bioeconomy" or "Bio-based Circular Economy." These policies are often linked to the United Nation’s Sustainable Development Goal 12, which aims to ensure sustainable consumption and production patterns. However, current urban and regional planning processes largely lack a systemic nutrient circularity perspective (Teleshkan et al. 2024; McGreevy et al. 2022). Instead, they often address nutrient-containing flows through fragmented approaches, dividing rural/agricultural strategies from urban/waste management strategies, each with separate actors and policies (Tamsma et al. 2024; Bremmer et al. 2020).

Two prominent global trends include promoting more sustainable agriculture in agri-food activities and increasing organic waste recycling in urban areas. While most policies are crafted at the national level, some have adapted to regional or city-specific needs (Gottinger et al., 2020). Notable examples include Finland's Circular Economy Roadmap, the USA’s Strategic Plan for a Sustainable Bioeconomy, Spain’s Integrated Waste Management Plan for Castilla-La Mancha, and Chile’s National Strategy for Organic Waste (Dietz et al. 2018; Vanhamäki et al. 2020).

Nutrient circularity policy development varies significantly worldwide, particularly in low- and middle-income countries, where the lack of research and tools for effective policymaking has led to fragmented strategies and insufficient planning (Ddiba et al. 2021; Nesme and Withers

2016). In South America, the interaction between urban and rural nutrient cycles is especially important, as it is the most urbanized region in the developing world and a leading global food producer (World Bank, 2018; Circular Economy Coalition, 2022). However, despite adherence to global agendas like the UN Sustainable Development Goals, progress in adopting nutrient circularity policies has been slow (Hernández and Céspedes 2020). Most South American cities continue to follow a linear approach to organic waste management, which exacerbates resource depletion and environmental degradation. Nearly all organic waste is sent to landfills that fail to meet international standards, contributing to significant environmental harm (Margallo et al. 2019). Current initiatives primarily focus on municipal waste management and the use of biomass for fertilizer or energy, both of which rank low on the waste hierarchy and biomass value frameworks (CEPAL et al. 2018; Hodson de Jaramillo et al. 2019).

1.6. This Research

1.6.1. Case Study Area

This "Introduction" chapter has outlined the shift toward urbanization, the theoretical and practical challenges and opportunities associated with sustainable urban development, and the importance of managing nutrient-containing flows in circular resource systems within cities and metropolitan areas. At the start of this chapter, the central question was posed: *How can nutrient circularity be effectively and systemically incorporated into sustainable urban development strategies?*

To address this question, it is crucial not only to consider *how* but also *where* these efforts should be concentrated. As previously discussed, South America is projected to experience some of the highest rates of urbanization in the coming years. This presents both significant and unique opportunities and challenges, alongside a pressing need to optimize current and future planning processes. Therefore, this research focuses on advancing nutrient circularity in South American metropolitan areas, with particular attention to Chile. The rationale for this selection is explored in greater detail in the following chapter, but an overview of the country is provided here.

Chile, the country with the highest Gross Domestic Product (GDP) per capita in South America, is classified as a high-income nation (CEPAL 2022). The contribution of agriculture, forestry, and fishing to Chile’s GDP has steadily decreased from over 10% in the 1960s to less than 4% in 2019, with most of this contribution now linked to food processing, particularly from fruit crops (Steen Nielse et al., 2012). Chile’s diverse geographical characteristics provide various agricultural opportunities, placing it 25th out of 113 countries in the Global Food Security Index. Chile scores highly in areas such as food safety net programs, access to financing for farmers,

nutritional standards, and food safety. However, challenges remain in public expenditure on agricultural R&D and per capita GDP (The Economist Group, 2019).

Rapid and sustained economic growth has come at a significant environmental and social cost, contributing to high greenhouse gas emissions, water pollution, and public health concerns (Pino et al. 2015). Despite efforts to improve waste management, Chile faces significant challenges in recycling and composting. Most recycling efforts in Chile have been driven by the informal waste-picking sector, private companies, and independent municipal initiatives (Valenzuela-Levi 2019a). In Gran Santiago, three municipalities—Vitacura and Nuñoa (for dry recyclable waste) and La Pintana (for kitchen waste)—have formal segregated collection systems. "Drop-off" collection points, or "clean spots" (puntos limpios), managed by municipalities or recycling companies, are another popular recycling method, though data on their collection rates are scarce (Rojas et al. 2013).

Recent scientific research in Chile has focused on various aspects of waste management, including population demand for recycling (Vásquez et al. 2014), multi-scalar waste flow analysis (Guibrunet et al. 2017), policies for informal waste-pickers (Navarrete-Hernandez and Navarrete-Hernandez 2018), urban agriculture as green urban space, life cycle assessments of waste management scenarios (Rojas et al., 2018), decentralized nutrient recovery technologies (Kraker et al., 2019), and factors influencing municipal recycling efforts (Valenzuela-Levi, 2019).

1.6.2. Metropolitan Region of Santiago

Chile's population has increasingly concentrated in Santiago, which held one-third of the national population by 1980 due to the country's challenging geography (Madaleno and Gurovich 2004). The Metropolitan Area of Santiago reflects both "implosion," through increased housing density and vertical growth, and "explosion," with sprawling development into peripheral rural areas (Fuentes & Pezoa, 2018). Though it occupies just 2% of Chile’s land, this region holds 40% of the population and generates 48% of the national GDP (CEPAL, 2017).

Historically, social housing projects expanded into the southern peri-urban region, home to Santiago's most fertile soils (Hidalgo Dattwyler, 2007; Silva, 2020). In the last decade, however, peripheral development has shifted northward (Inostroza, 2017). Madaleno & Gurovich (2004) outline Santiago’s urbanization history and its social and economic impacts on nearby farmlands, particularly changes in land tenure and land use. The southern municipalities, where much of the development occurred, still support small-scale agriculture, including

communal orchards and animal husbandry in areas like La Pintana (Zamora et al., 2012; Silva, 2020).

The Metropolitan Region of Santiago de Chile generates the highest volume of waste in Latin America (Ailyn Rojas et al., 2018). Waste management in the city follows a common regional pattern: increasing waste quantities, limited resource recovery, and a heavy reliance on landfilling as the primary disposal method. An estimated 98% of household waste is sent to one of the region's five landfills, while the average Separate Collection Rate for recycling and composting is only 1.7% (Ministerio del Medio Ambiente, 2012, 2018; Valenzuela-Levi, 2019). Although recycling rates are highest in the capital, Santiago, so too is per capita waste generation (Rojas et al., 2018). Approximately 57% of domestic solid waste in the region is organic, with around 75% of that consisting of food waste, and the remainder from gardens (Martínez, 2011).

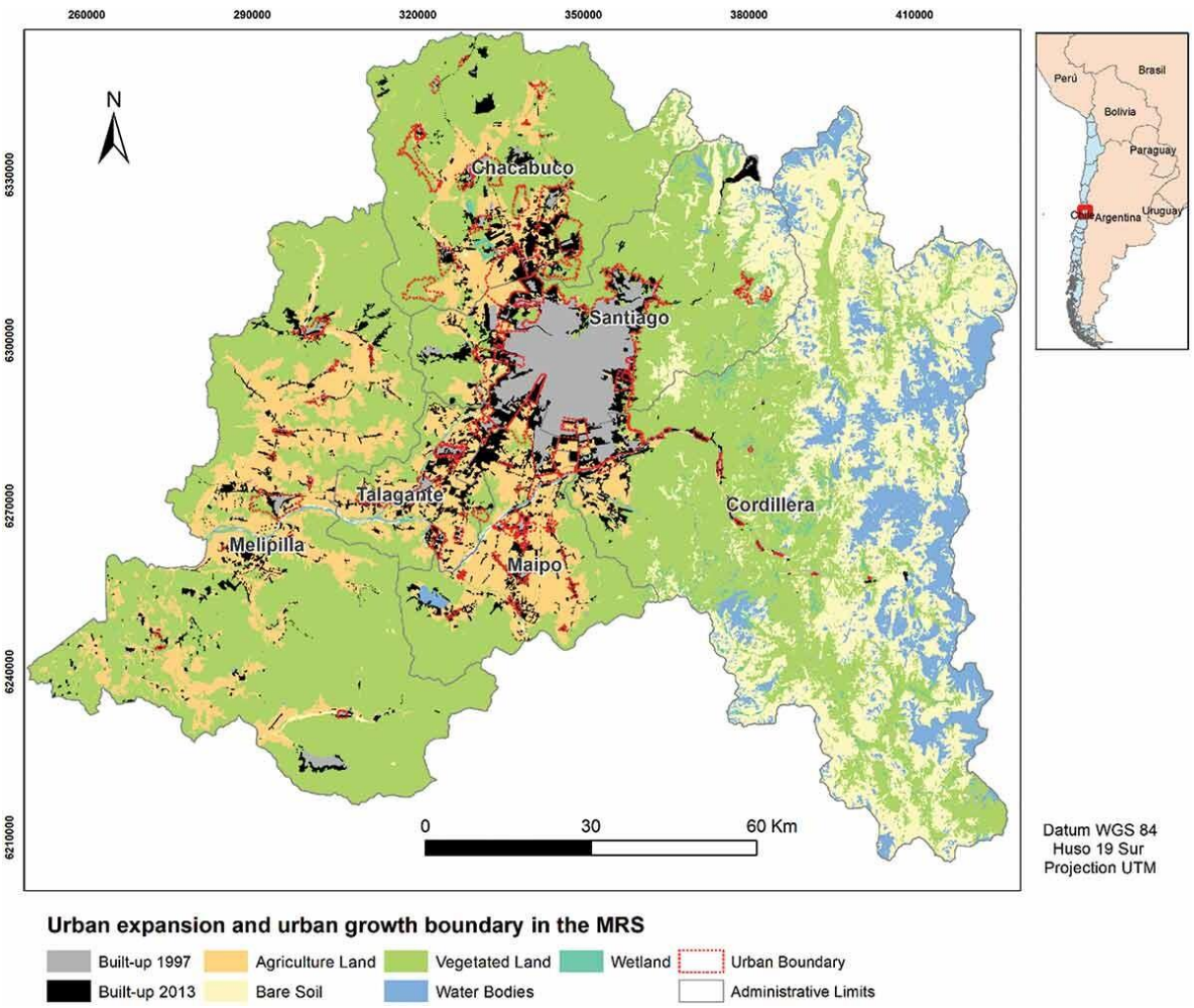

Figure 4. Change in a built-up area in the metropolitan region of Santiago (MRS), Chile, between 1997 and 2013 and the urban growth boundary. Source: Schuster et al. 2021.

In Santiago, most waste management campaigns have traditionally focused on inorganic materials such as plastics, metal, and glass (CONAMA, 2006; SEREMI Región Metropolitana, 2018). However, there is significant potential for alternative valorization of nutrient-containing flows, with recent studies demonstrating economically viable nutrient recovery options for the district (de Kraker et al., 2019). Aguas Andinas, Chile's largest sanitation company, collects and treats 100% of the region's wastewater, applying 44% of the resulting biosolids to agricultural soils and using biogas generated from the process to supply electric and thermal energy to nearby cities (Baurier, 2018).

Recent efforts to enhance sustainability include the establishment of a national climate change agency ("Agencia de Sustentabilidad de Cambio Climático" in Spanish) and the creation of the National Circular Economy office within the Ministry of Environment (see Figure 5). Recently, the Regional Strategy for Solid Waste in the Metropolitan Region has broadened its scope to promote recovery programs for the organic fraction of urban solid waste, complementing initiatives led by the National Circular Economy office. The latter is responsible for implementing the Extended Producer Responsibility Law, which focuses on recovering inorganic waste, as well as designing a national strategy for organic waste valorization (Gobierno de Chile 2021).

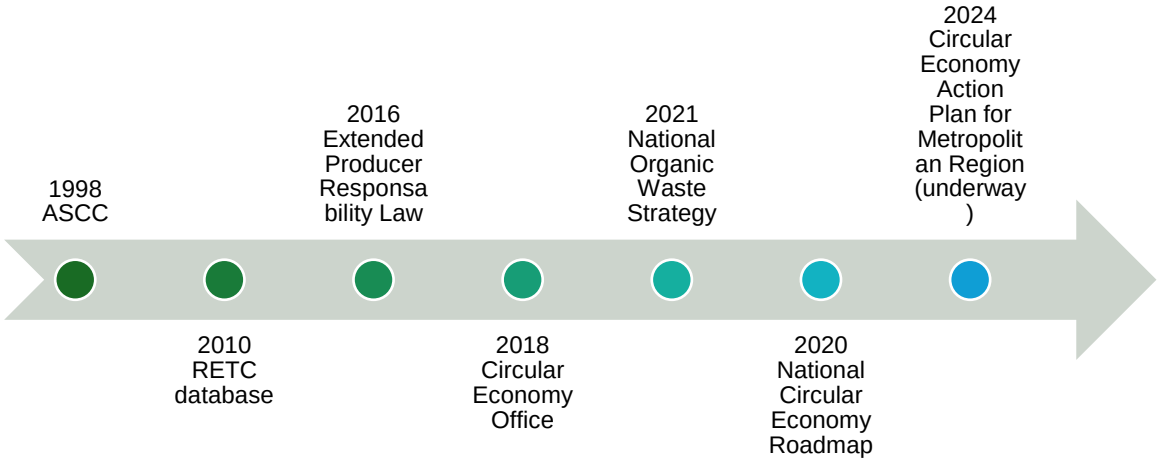

Figure 5. Recent government initiatives in Chile related to the Circular Economy. (Own elaboration)

The Ministry of Environment recently introduced the "Organic Waste National Strategy" (ENRO), which aims to recycle 66% of organic waste by 2040 (Ministerio de Medio Ambiente 2021). The plan outlines several key goals:

- Recover 30% of all municipal organic waste
- Equip 500,000 families with composting and vermicomposting tools
- Implement composting and vermicomposting in 5,000 educational institutions

- Introduce composting and vermicomposting in 500 neighborhoods through the "Quiero mi Barrio" program
- Ensure 50% of public institutions separate and valorize their organic waste
- Compost all organic waste in urban parks managed by the Ministry of Housing and Urbanism

The Circular Economy Action Plan for the Metropolitan Region (Deuman 2022) was in progress during the development of this research, and key stakeholders involved in that process were involved in this study.

1.6.3. Research Steps / Articles

As highlighted in Section 1.2, effective research on nutrient flows, urban metabolism, and resource circularity for use in urban planning should account for all relevant subsystems. This often necessitates the inclusion surrounding rural areas or functional hinterlands typically encompassed within larger metropolitan regions. Therefore, regarding the “how” aspect of our research question, this research focuses on the metropolitan scale. Furthermore, this research adopts a systemic perspective by examining the 'agro-food-waste system' and its subsystems. This is particularly pertinent in the context of metropolitan planning, where terms such as 'food system' or 'agrifood system' are often narrowly interpreted, focusing on aspects like nutritional value, access, or food safety, without fully addressing the broader activities and flows crucial for nutrient circularity. Additionally, this study refers to the relevant material flows as 'nutrient-containing flows' (or simply 'nutrient flows' for readability), rather than using terms like 'biological' or 'organic' flows, which may exclude inorganic components such as mineral fertilizers.

In this research, the first step in integrating nutrient circularity into urban strategies involves identifying and measuring the factors that influence nutrient-containing flow management in urban and regional development. These factors inform a city or region's capacity to implement effective strategies and enable comparisons over time or between areas. The assessment of these factors allows planners to identify system strengths and weaknesses for strategic resource management. The second step focuses on conducting a planning-oriented assessment, integrating urban metabolism and planning principles to evaluate these factors across multiple dimensions, generating insights for sustainable strategy development. Finally, incorporating diagnostic findings into ongoing strategic planning requires synthesizing these insights with existing policies and stakeholder interests, presenting them in a clear, accessible manner to facilitate stakeholder engagement in exploring future resource management scenarios.

The following chapters of this manuscript delve into these steps, each presented as an independent scientific article (see Figure 6), where their application and evaluation are explored through the case study of the Metropolitan Region of Santiago, Chile. Of the three articles, the first has been published in *Resources, Conservation & Recycling*, the second was submitted and is currently under post-review revision for publication in *Journal of Cleaner Production,* and the third is being prepared for submission to *Sustainability Science*. In the final chapter of this manuscript, 'Discussion & Conclusion,' the results, implications, and limitations of these three research steps are integrated and discussed.

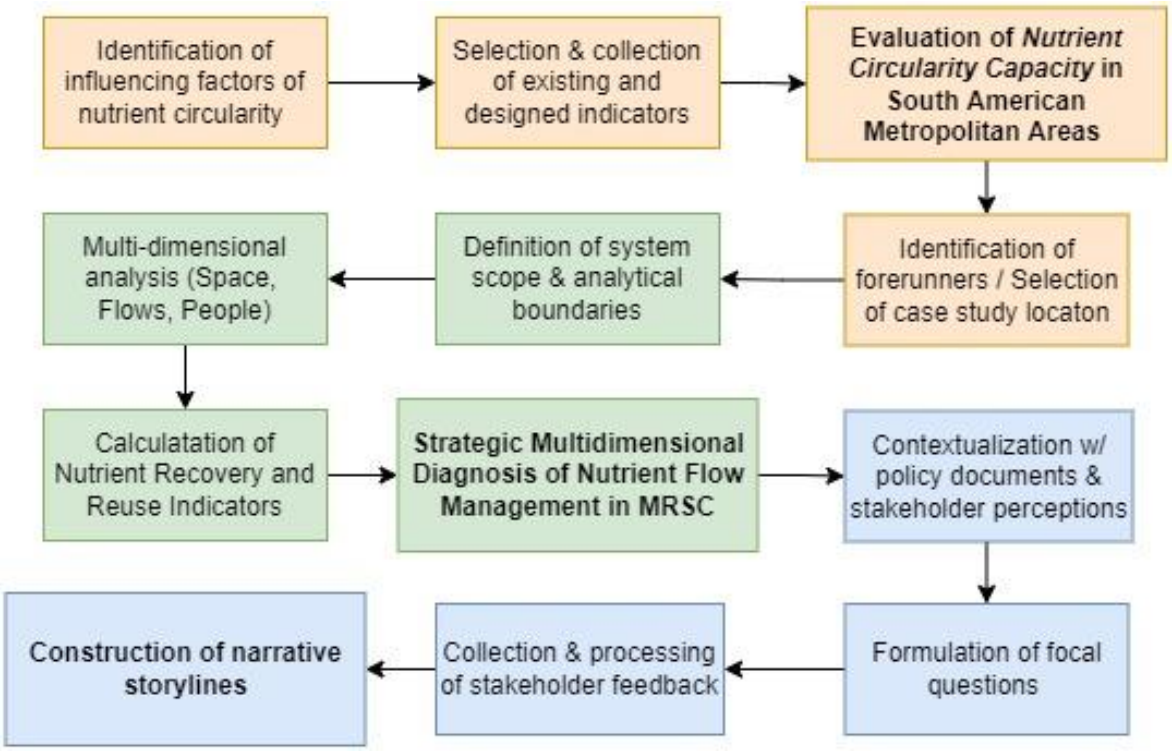

Figure 6. Overview of research methodology. Each color represents a different research step organized into its own chapter / article.

The first step in addressing nutrient circularity is identifying the factors that influence the management of nutrient-containing flows and determining how these factors can be measured. This process involves a comprehensive understanding of nutrient circularity within the context of urban and regional development. The state of these factors will inform a city or region's capacity to develop and implement effective nutrient circularity strategies. By measuring these factors, it is possible not only to assess a city or region's current capacity but also to compare these findings with those of other areas or evaluate its progress over time. This analysis enables planners and policymakers to identify strengths and weaknesses in their existing systems, allowing them to strategically incorporate these insights into future diagnostic and planning activities focused on sustainable and circular resource management.

Note: This article has been published as: Fleitas Girett, Alma; Wassenaar, Tom; Pabon-Pereira, Claudia (2023): Assessing nutrient circularity capacity in South American metropolitan areas. In *Resources, Conservation and Recycling* 197, p. 107085. DOI: 10.1016/j.resconrec.2023.107085.

2. ASSESSING NUTRIENT CIRCULARITY CAPACITY IN SOUTH AMERICAN METROPOLITAN AREAS

2.1. Introduction

After decades of linear agri-food production and consumption systems, countries around the world are prioritizing the need for more sustainable models of biological resource management (Billen et al. 2021). Increasing food demand, volatile costs and provision of chemical fertilizers, and the negative externalities of linear waste disposal are all incentivizing societies to reduce the loss of nutrient-containing materials, while also increasing recovery from so-called waste streams for reincorporation in local productive activities (Drechsel et al. 2018; Harder et al. 2021b). This goal is often referred to as *closing nutrient cycles* or increasing *nutrient circularity*.

When adapting nutrient circularity concepts to political agendas, some governments have adopted terms like “Circular Bioeconomy” or “Bio-based Circular Economy”. On an international level, these concepts are often linked to the United Nation’s Sustainable Development Goal 12 “to ensure sustainable consumption and production patterns”. Generally, two strong trends can be observed internationally: the promotion of sustainable agriculture practices in food production, and recycling of organic waste in urban areas. Though most have been crafted at a national level, some policies have aimed for a more regional or city application (Gottinger et al. 2020). Some examples include the Finnish Roadmap to a Circular Economy, the Strategic Plan for a Thriving and Sustainable Bioeconomy of the USA, the Integrated Waste Management Plan of Castilla, La Mancha (Spain), and the National Strategy of Organic Waste in Chile (Dietz et al. 2018; Vanhamaki et al. 2019).

The degree of development and implementation of strategies varies widely around the world. In this research, South America was chosen as the study area considering its high economic dependency on agricultural activities, low coverage of waste management infrastructure, increasing levels of urbanization through agglomerations, and finally, lack of existing similar research (Coq-Huelva and Asián-Chaves 2019; Madaleno and Gurovich 2004; deMiguel et al. 2021). These characteristics can support various socio-technical transition pathways, but the adoption of nutrient circularity policies and strategies at any level in South America has been slow, despite adherence to global agendas like the UN SDGs (Hernández and Céspedes 2020). Existing initiatives tend to focus on municipal organic waste management or the use of biomass as fertilizer or energy source (CEPAL et al. 2018; Hodson de Jaramillo et al. 2019), both of which lie low on the waste hierarchy and biomass value frameworks. Moreover, research and tools to support strategy development are generally lacking for low and middle-income countries (Ddiba et al. 2021; Nesme and Withers 2016), which in turn can limit the development of strategic visions and planning.

Metropolitan areas (MAs) represent territories that concentrate resources important for socio-economic transitions, such as human capital, research institutes, economic development, and institutional presence, while often containing the spatial diversity necessary for resource revalorization opportunities (Modrego and Berdegué 2015). While these areas tend to present greater levels of innovation and quality of public services, they also present elevated levels of social inequality and contamination (OECD 2020). The intensity of consumption activities in urban agglomerations requires food imports, while simultaneously generating a concentrated flow of emissions, especially as food and sanitary waste. For logistic and financial feasibility, they're usually disposed of within the same MA, leading to "nutrient sinks" that are increasingly being assessed for their utilization potential within regional nutrient cycles (Kraker et al. 2019; Velenturf and Purnell 2017; Wang et al. 2021; Wielemaker et al. 2019). Considering that South America is both the most urbanized continent in the developing world (over 80%) and a top producer of the world's food (World Bank 2018; Circular Economy Coalition 2022), the interaction between urban and rural nutrient cycles is of great relevance. Finally, MAs and similar scales of territory allow for an effective combination of top-down strategic planning while also applying varying degrees of participatory governance and co-creation (Medeiros and van der Zwet 2020).

Scientists have been increasingly interested in nutrient circularity in MAs. Assessment frameworks have been developed (Billen et al. 2021; Koppelmäki et al. 2021; Papangelou and Mathijs 2021), with a growing focus on nutrient recovery opportunities from urban sanitation flows (Kraker et al. 2019; Trimmer et al. 2019; Wielemaker et al. 2020). Though the composition of systems can vary according to the scope of analysis, studies generally include food production, consumption, and/or waste treatment activities of the "agri-food-waste system" (Harder et al. 2021a; van der Wiel et al. 2019). Studies have also identified a variety of drivers and barriers linked to the transition to circular resource management (Gottinger et al. 2020; Lazurko et al. 2018; Nesme and Withers 2016), but the significance of specific factors influencing the transition depends greatly on the context in which they are assessed. Authors recognize that theories and models developed in highly developed countries, like of the European Union, can be challenging to adapt to different conditions, such as those of South America (Tura et al. 2019), making it difficult for local decision-makers to assess which factors may be more relevant or important for their context or objectives (Ddiba et al. 2021; Queste and Wassenaar 2019). Moreover, although authors have studied the reintegration of urban flows into rural areas (Wang et al. 2021; van der Wiel et al. 2019; Wassenaar et al. 2014), these works tend to be largely from a technical and material flow perspective (Vayssières and Rufino 2012; Rosemarin et al. 2020), and/or limited to the contexts of European countries (Do et al. 2021; Gottinger et al. 2020).

The transition to more sustainable nutrient management systems requires the integration of social, environmental, and economic dimensions from varying perspectives, while also incorporating local actors and values (Harder et al. 2021b; Poponi et al. 2022; Petit-Boix and Leipold 2018; Gottinger et al. 2020). This study proposes a framework for measuring Nutrient Circularity Capacity (NCC), referring to a context's potential to develop and implement circular nutrient initiatives, based on existing characteristics. The framework first defines the material and organizational characteristics that influence NCC and then selects indicators to measure them. To assess NCC, we applied this tool to South American MAs.

2.2. MATERIALS AND METHODS

2.2.1. Determining Nutrient Circularity Capacity (NCC)

Determining capacity for nutrient circularity involved assessing the existing local conditions of nutrient flow management which may be supporting or impeding the transition to more circular management systems. This includes both the recovery and reutilization of nutrients. Considering the gap between academic research and policy, the approach aimed to be operational for a variety of actors and contexts to inform and empower stakeholders working with nutrient-containing material flows (Deconinck et al. 2022; Martin et al. 2019; Snilstveit et al. 2016). With these goals in mind, a methodology was established (Figure 1) that consists of four main steps: a) Identification of environmental, technical, economic, social, and political factors that influence the development and application of nutrient circularity strategies, b) Selection of indicators that, together, provide insight on the state of their respective factors, c) Collection and processing of local data to inform these indicators, and d) Scoring of values to compare NCC for each MA.

2.2.1. Identification of Influencing Factors (IF)

To identify elements related to nutrient circularity, a literature review was carried out using the Scopus database and European Union publications. Specifically, the terms “enablers”, “drivers”, “barriers” and/or “obstacles” were searched for in relation to “circular economy”, “circular bioeconomy”, “resource recovery”, and “sustainable resource management”. Finally, the articles were narrowed down to recency from the last 5 years (2017-2021) and on high relevance to the chosen topics based on their abstracts, resulting in a selection of 21 key documents. This selection produced almost 400 elements ranging across environmental, socio-economic, and political-legal dimensions (summarized in Appendix A). Though these elements were collected from literature, 10 of the 21 key articles utilized methodologies that included stakeholder consultation and validation.

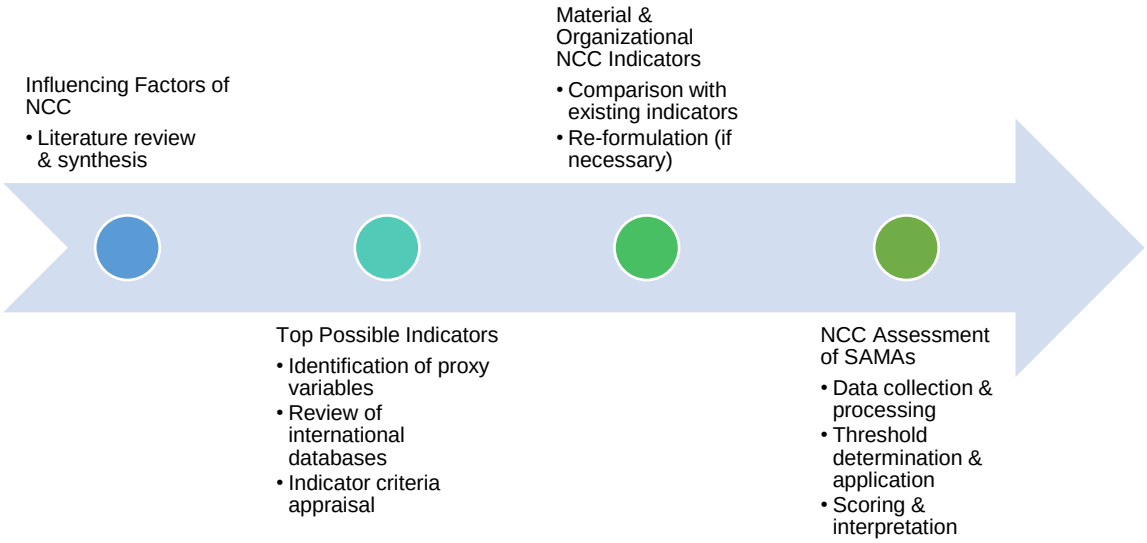

Figure 1 Schematic overview of the methodological steps and outcomes of this study.

This initial inventory was then revised, organized, and synthesized considering features specific to the agri-food system, such as agricultural activities, technologies, and urban infrastructure. This iterative process helped bridge possible gaps caused by the limited literature specific to nutrient-containing material flow management systems. Elements were first categorized by distinguishing related topics, and then each group was organized by degree of detail of information. This organization of elements led to a hierarchy of three levels: Central Themes, Influencing Factors, and Indicators. Information within the same hierarchy level was synthesized by identifying overlaps and gaps, resulting in more consolidated, congruent concepts.

2.2.2. Selection of NCC Indicators

Next, since IFs are not directly observable or measurable, *proxy variables* were identified. Still, these were found to be too broad for the objectives of this study and were therefore again linked to another set of more well-known, pragmatic variables called *possible indicators*, without contemplating restrictions of geographic setting or availability. Next, international databases and indexes were consulted to develop a list of relevant, *existing indicators* that could also be linked to the IF. Databases included FAO Stat, World Bank, International Development Bank, and United Nations Economic Commission for Latin America and the Caribbean (ECLAC), as well as indexes such as the Global Innovation Index (Cornell

University, INSEAD, and WIPO 2020) and Environmental Performance Indicator (Wendling et al. 2020).

Considering the vast possibility of variables and indicators that could derive from these processes, a multi-criteria analysis assessed the possible indicators with pre-selected criteria that could allow the selection of "top possible indicators". Cash et al. (2003) found that the salience, credibility, and legitimacy of scientific information are key to effectiveness in decision-making, and van Oudenhoven et al. (2018) included feasibility as an additional crucial criterion (Figure 2). Because this assessment is not aimed at directly informing specific political decisions or strategies, legitimacy was not considered a key criterion of this assessment and stakeholders were not included for the selection of indicators, but should be for more localized research and policy. Furthermore, all data used to inform indicators was collected from reputable, official sources, such as recognized international organization databases and official government sources (national surveys, national statistic reports, etc.), so credibility was considered satisfactory.

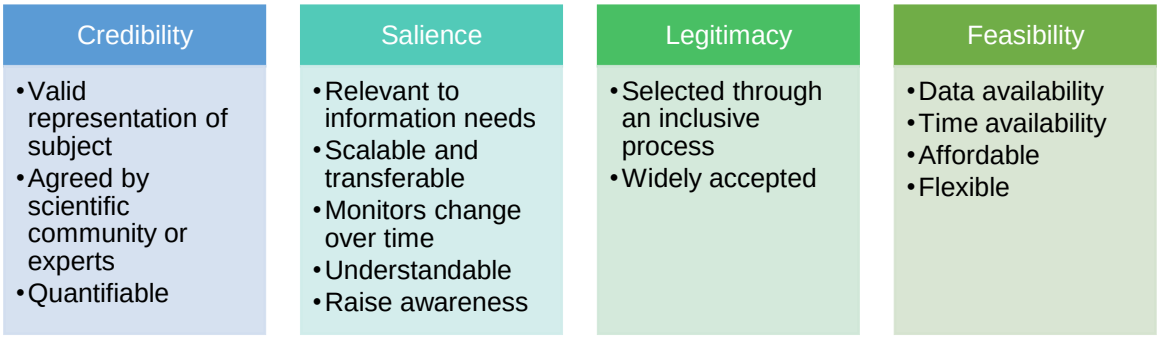

Figure 2. Criteria used for indicator assessment, based on van Oudenhoven et al. (2018) and Cash et al. (2003)

IF are not independent of each other but are instead part of a complex system of varying degrees of dependence and influence. These interdependencies were mapped and incorporated into the NCC indicator appraisal process. **Salience** was split into two types: direct salience, which judged the representativeness of each possible indicator concerning its respective influencing factor, and global salience, which considered how each influencing factor could be representative of other influencing factors based on internal influences. Multiple weights of global salience were tested to determine the impact of this variable in the resulting indicator selection. Meanwhile, **feasibility** was measured through four characteristics: availability of information as an indicator, as raw data, at the desired geographic scale, and recency of information. A more detailed description of this step can be found in Appendix B.

Finally, the highest-scoring possible indicators were selected, aiming for a selection short enough to allow a feasible analysis yet long enough to include as many influencing factors as possible. Once the final selection of indicators was established, this list was compared to the list of *existing indicators* that was previously developed. The indicators that could be matched to existing ones were further evaluated to assess credibility, feasibility, and salience. Alternatively, indicators that couldn't be matched were re-formulated to link their original compositional data to existing information that could then be re-processed to create a similar, satisfactory indicator.

2.2.3. Data Collection and NCC Scoring

The limits of a metropolitan area can be difficult to identify and are often not consistently defined. Therefore, approximate geographical boundaries were established for all MAs by combining two published data sources; a 20 km buffer was applied around the revised 1 km resolution Urban Extent Polygons of the GRUMP project (CIESIN et al. 2021), subsequently limiting this buffer to the area with less than one hour travel time to the city (1 km resolution map by Weiss et al. 2018). For data collection purposes, the closest-matching administrative boundary was developed by grouping districts and/or departments/regions identified in literature as components of the metropolitan area (described in Appendix C).

First, existing indicator values were gathered from their respective sources. The remaining indicators were then informed through the review of national or regional surveys, national statistical databases, and government reports regarding agricultural activities and waste management systems. When data was not available within these sources, reports were reviewed from waste treatment companies and local experts were contacted. Data corresponding to the year 2021 was collected, or the closest following year if 2021 was not available. The full list of references for this step can be found in Appendix C.

Tentative thresholds of "high", "medium" and "low" categories were determined for each indicator to provide a general interpretation and comparison of nutrient circularity capacity among SAMAs. Organizational capacity indicator thresholds were based on the numerical distribution of values from the full global datasets. Material capacity indicators have less data availability and can be highly context-specific, so expert-based criteria were used to determine thresholds. These are further explained in Appendix E. These categories then allowed the application of a simple aggregated scoring system (low=0, medium=1, high=2). During this process, the distinction between two dimensions of NCC, material and organizational, was

considered the most robust manner for interpreting the results considering the differences in underlying factors that shape such capacities, as well as in the possibilities for future interventions or studies.

2.2.4. Metropolitan areas of South America

To illustrate the potential of the NCC appraisal, a non-exhaustive set of South American metropolitan areas (SAMAs) was selected. There are 12 sovereign states in South America, but only 10 are considered to have a “large metropolitan area” according to the OECD (2020). All 10 countries were included to reflect the continent’s geographic diversity, and each country’s most populated MA area is listed below, from most to least populated.

1. Sao Paulo, Brazil
2. Buenos Aires, Argentina
3. Lima, Peru
4. Bogotá, Colombia
5. Santiago, Chile
6. Caracas, Venezuela
7. Quito, Ecuador
8. Asunción, Paraguay
9. Montevideo, Uruguay
10. Santa Cruz de la Sierra, Bolivia

2.3. RESULTS

2.3.1. Characterizing and Measuring NCC

Figure 3 presents the final list of 12 IF across 4 central themes*:* Material Flow Potential, Food & Feed Value Chain Characteristics, Knowledge Base, and Institutional Support. These influencing factors are explained in further detail in Appendix D. The influences between IFs were mapped to represent the interdependence of these factors, as well as to highlight how one factor could be representative of other “downstream” factors.

Next, the definition of each IF was used to identify 33 *proxy variables* that were linked to 39 *possible indicators*. These were then appraised through a multi-criteria analysis which yielded three possible rankings of the most feasible, representative indicators of NCC. The ranked lists showed strong overlap and a total of 11 possible indicators were selected, covering two-thirds of all IFs. These 11 were then compared with the 56 existing indicators that were identified through the international database review. Of the 11 top possible indicators, 6 were matched with satisfactory existing indicators (Table 1). These indicators measure organizational capacity at a national level and were deemed appropriate for this study as it focused on the largest SAMAs which are mainly located in capital cities. Such areas tend to concentrate national resources related to research and development, knowledge transfer, innovation, sustainability policy, etc. (Da Cruz et al. 2020; Gleeson and Spiller 2012; Xue et al. 2022).

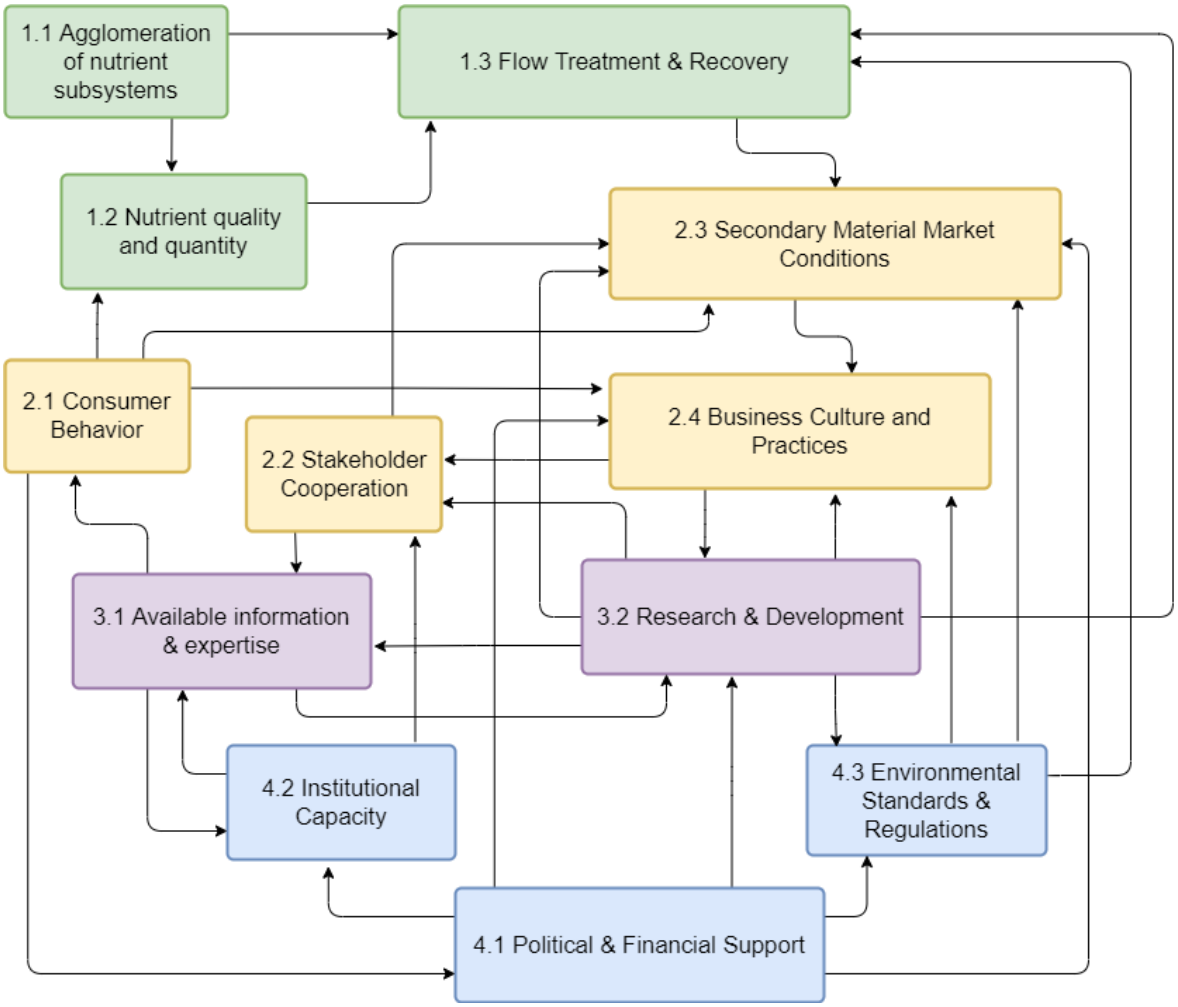

Figure 3. The 12 NCC Influencing Factors identified in this study, including their interdependencies and central themes. Arrows represent internal influences. Each color represents a Central Theme: green represents Material Flow Potential, yellow represents Food and Feed Value Chain Characteristics, purple represents Knowledge Base, and blue represents Institutional Support.

For the remaining *top possible indicators*, a matching existing indicator was either not identified or determined unsatisfactory due to available scale or recency of information. These indicators all related to *material capacity* at a local scale, and were re-formulated while adhering to the feasibility, credibility, and salience criteria. For example, one top possible indicator for material potential was *"distance from urban center to agricultural land"*, linked to the IF 1.1 "Agglomeration of nutrient subsystems". Since data was not readily available to inform such an indicator, instead, the IF was reexamined by considering the original description of this IF, re-determining the variables linked to such a condition, and finally selecting the most functional variables that could meet the criteria of credibility, salience and especially feasibility. The result of this case was the formulation of the indicator *"hectare of surface area dedicated to crop production per capita"*. Ultimately, 5 indicators were formulated and added to the final selection (Table 1).

Table 1.Description of final selection of NCC indicators.
Formulated material indicators are shaded green, while existing organizational indicators of NCC are shaded blue.

Influencing Factor	Indicator	Composition	Source
1.1 Agglomeration of nutrient subsystems	Hectare of surface area dedicated to crop production per capita	Surface area dedicated to crop production in MA / total surface area of MA	National Agricultural Census, Agricultural Indicators from governmental statistical agencies
	Monogastric livestock heads per capita	Heads of swine * TLU of swine / Population in MA Heads of chicken * TLU of chicken / Population in MA	National Agricultural Census, Agricultural Indicators from governmental statistical agencies
1.2 Nutrient Flow Quality and Quantity	Percentage of organic solid waste that is collected separately	Organic MSW collected separated / MSW generation rate * Percentage of organic fraction of MSW	Municipal waste management reports, Sanitation indicators from governmental statistical agencies, National Environmental Management Reports
	Percentage of discharged wastewater that receives (at least) secondary treatment	Volume of treated wastewater / Volume of wastewater generated per day	Sanitation indicators from governmental statistical agencies, National Environmental Management Reports
1.3 Flow Treatment and Recovery Options	Percentage of sludge waste that is treated for nutrient recovery	WWTP sludge applied to soil or used to develop fertilizer / WWTP sludge generated	Wastewater Treatment Plant Reports, National Environmental Management Reports
2.2 Stakeholder Cooperation	Innovation Linkages	"The Innovation linkages subpillar draws on both qualitative and quantitative data regarding business/university collaboration on R&D, the prevalence of well-developed and deep clusters, the gross R&D expenditure financed by abroad as a percentage of GDP, and the number of deals on joint ventures and strategic alliances. In addition, the total number of Patent Cooperation Treaty (PCT) and national office published patent family	Cornell University et al. 2020

Influencing Factor	Indicator	Composition	Source
		applications filed by residents in at least two offices proxies for international linkages."	
3.1 Available information and expertise	National Spatial Data Infrastructure Development Index (CEPAL STAT)	"The indicator is generated from a methodological tool "questionnaire" that is addressed to the representative of each member country. This questionnaire is made up of categories that allow evaluating the state of SDI implementation, these are: institutional aspects, human resources, technology, geographic information and norms - standards.	ECLAC Statistics and Economic Projections Division 2020
3.2 Research and Development	Knowledge Creation	"The first sub-pillar refers to the creation of knowledge. It includes five indicators that are the result of inventive and innovative activities: patent applications filed by residents both at the national patent office and at the international level through the PCT; utility model applications filed by residents at the national office; scientific and technical published articles in peer reviewed journals; and an economy's number of articles (H) that have received at least H citations."	Cornell University et al. 2020
	Country GSSEA: Agricultural knowledge and innovation system (IDB)	"Budgetary transfers that finance research and development (R&D) activities related to agriculture, agricultural vocational schools and agricultural programs not specific to individual situations, and data collection and information dissemination networks related to agricultural production and marketing. Composed of two sub-components: Agricultural Knowledge Generation and Agricultural Knowledge Transfer."	Inter-American Development Bank 2020
4.1 Political and Financial Support	Existence of circular economy policies	"National circular economy policy (national level): this category includes any national circular economy policies already in place as well as national green growth or sustainable development strategies which integrate circular economy principles."	Chatham House 2021
4.3 Environmental Standards and Regulations	Existence of extended producer responsibility policy	"Extended producer responsibility policy (national and state level): this category relates to policies that place the responsibility for the environmental impacts of products throughout the product life cycle to producers and is often applied to the collection, processing and re-utilization of waste."	Chatham House 2021

2.3.2. NCC in South American Metropolitan Areas

Once indicators were selected, data was collected and processed for the SAMAs. During this process, it became clear that very limited data was available for Caracas, Venezuela, so this MA was excluded. Furthermore, upon verifying the indicator “6. Existence of Extended Producer Responsibility Policy”, all 10 studied areas were found to have some degree of this, so it was ultimately excluded from the final assessment. Also, the indicator “4. GSSEA: Agricultural knowledge and innovation system” was ultimately calculated as a percent of TSE (Total Support Estimate) to find relative values for each country. For the indicator “11. Percentage of sludge waste that is treated for nutrient recovery”, the lack of available information regarding the recovery of any sludge was represented by 0%, assuming that no such recovery occurs. Indicator values are displayed in Table 2.

These indicator values indicate that Uruguay had the highest overall level of organizational capacity in comparison to other SA countries due to high levels of government support for innovation, knowledge creation, and development of national circular economy policies. Countries with the lowest organizational capacities were Paraguay and Bolivia, both of which invest little in knowledge creation and innovation, nor have circular economy policies in place. Santiago, Montevideo, and Santa Cruz de la Sierra had the highest material capacity, while Asunción is again amongst the areas of lowest capacity, directly related to the very low levels of agricultural activities in the metropolitan area, similar to Sao Paolo and Lima, as well as deficient solid and liquid waste management systems. Montevideo, Uruguay was identified as the regional forerunner of nutrient circularity capacity in SAMAs, achieving a total NCC score of 14 of 20 possible points, while Asunción, Paraguay was found to be lagging in comparison to other areas in the region, with a total NCC score of 3 of 20 (Figure 4). While these two cases showed sharp differences, the average score across all areas was 9 points while the median was 10.

Table 2. NCC Indicator raw data values for 9 SAMAs. Red-shaded cells indicate values categorized as "low", while green-shaded cells indicate "high" values. Cells with no shade were found to be in between threshold limits, considered a "medium" in scoring. Data sources are listed in Table 1 and Appendix C.

NCC Indicators		Sao Paulo, Brazil	Buenos Aires, Argentina	Lima, Peru	Bogotá, Colombia	Santiago, Chile	Quito, Ecuador	Asunción, Paraguay	Montevideo, Uruguay	Santa Cruz de la Sierra, Bolivia
Material Flow Indicators	Ha of crop production in MA per capita	0.007	0.012	0.002	0.003	0.031	0.007	0.003	0.114	0.067
	Monogastric livestock units per capita	0.001	0.033	0.077	0.005	0.110	0.021	0.000	0.066	0.070
	Percentage of organic solid waste that is collected separately	2.5%	0.0%	0.0%	7.7%	0.8%	1.6%	0.0%	3.3%	1.6%
	Percentage of discharged wastewater that receives (at least) secondary treatment	64.3%	15.2%	18.4%	26.7%	100.0%	1.9%	11.0%	43.0%	31.0%

	Percentage of sludge waste that is treated for nutrient recovery	0.0%	100.0%	0.0%	100.0%	68.0%	55.0%	0.0%	0.0%	0.0%
Organizational Indicators	GII: 5.2 Innovation Linkages	21.4	16.0	16.5	15.5	17.4	13.4	14.3	16.8	13.3
	National Spatial Data Infrastructure Development Index (CEPAL STAT)	36	35	35	37	32	39	28	35	38
	GII: 6.1 Knowledge Creation	20.6	12.9	6.7	9.4	17.4	7.2	2.7	11.7	4.4
	Percentage of TSE dedicated to GSSEA	33.3%	-1.8%	8.5%	5.8%	11.3%	5.5%	42.3%	20.6%	0.4%
	Existence of National Circular Economy Policy	No	No	Yes	Yes	Yes	Yes	No	Yes	No

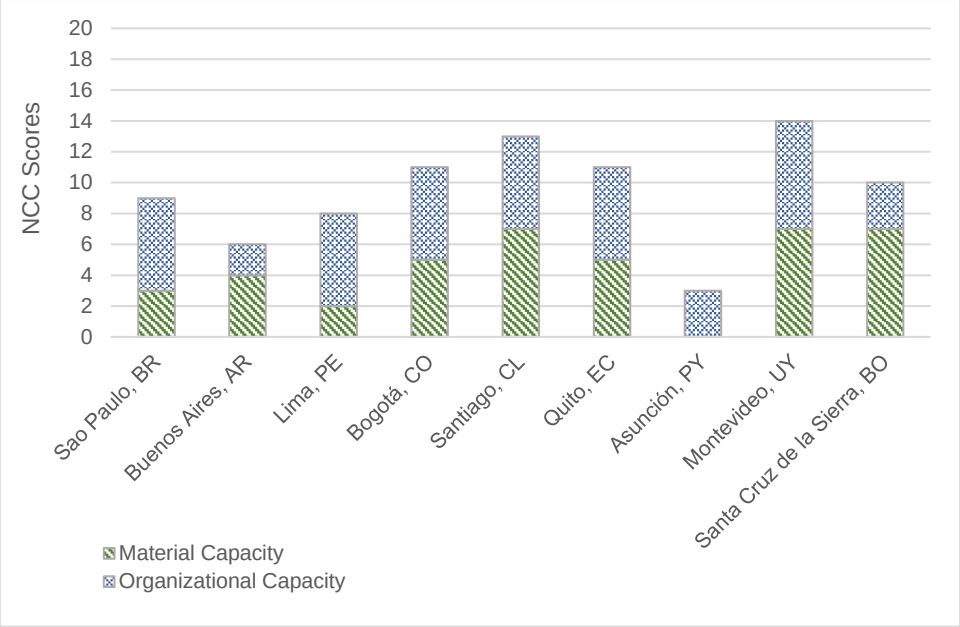

Figure 4. NCC Scores for material, organization, and total NCC for each studied area.

2.4. DISCUSSION

Linear agri-food-waste systems have led to disrupted local nutrient cycles, which often manifests as a disconnection between nutrient-demanding agricultural activities in peripheral rural areas and nutrient-supplying consumption activities in urban centers. Though research and policies are being developed to address these issues, they are limited to specific perspectives, objectives, and contexts. The proposed framework allows actors from different contexts to consider the multitude of factors that influence their capacity to improve the management of nutrient-containing flows. Furthermore, by applying this tool to South American metropolitan areas, we demonstrate how this assessment can highlight local gaps and priority areas affecting nutrient circularity.

2.4.1. Adapting the goals of nutrient circularity from international theories to local experiences

This study was able to synthesize hundreds of factors found to affect circular resource management systems into a comprehensive set of 4 Central Themes, 12 Influencing Factors, and 11 Indicators that can be assessed in any context. These findings are based on research from multidisciplinary perspectives on transitioning to sustainable economic and resource management systems. Studies have continually highlighted the importance and necessity of incorporating multiple perspectives to develop a comprehensive understanding of the transition to more circular economic and resource-management systems (Gottinger et al. 2020; Iacovidou et al. 2020). In the realm of sustainable management of nutrient-containing

flows, studies have either examined the conditions regarding the transition to more sustainable agri-food systems (Farooque et al. 2019; Borrello et al. 2016; Kardung et al. 2021; Barquet et al. 2020) or have aimed to measure the existing circularity of such systems (Koppelmäki et al. 2021; Papangelou and Mathijs 2021; Tanzer and Rechberger 2020; Harder et al. 2021b). Rarely have these two objectives overlapped, nor considered multi-dimensional factors, with recent exceptions like (Poponi et al. 2022) and (Velasco-Muñoz et al. 2021).

Furthermore, these concepts were made measurable through 11 indicators that can be determined using preexisting information that many areas have available but haven't yet exploited for this objective. While these works provide a variety of indicators that can intricately measure a variety of highly relevant aspects of nutrient circularity, they rely on data that is not currently available, instead depending on the generation of data following an assortment of methodologies from multiple academic references. More applicable frameworks have been developed through European regional planning projects such as the *Rural Urban Nexus* project of the German Federal Environmental Agency (Burger and Kuhn 2018) and the *REPAiR – REsource Management in Peri-urban Areas* EU Horizon 2020 project (Taelman et al. 2018), which included stakeholder engagement workshops. While the projects' results overlap with those of this study, they are still strongly influenced by the context for which they were developed, thus not as appropriate for areas in developing countries. Furthermore, this study is unique in that it acknowledges the inter-dependences *between* factors to select the most representative indicators.

Though the influence *between* factors was considered, factors that *indirectly* influence NCC were not explicitly measured. Such factors include geography, climate, income inequality, education levels, economic systems, sociocultural norms, and practices, among others (Tseng et al. 2019; Patel et al. 2021; Gottinger et al. 2020). While this influence is indirectly considered through the variables that inform the IF indicators, discerning the respective influence of these underlying conditions is beyond the scope of this study. This framework focuses attention on influencing factors to be further assessed before designing strategies, through thorough and participatory processes. In such further assessments, indirect, underlying factors may be highlighted.

Since high salience and credibility were inherent to the indicator formulation process, the selection of indicators was strongly associated with the appraisal of feasibility, providing both a strength and weakness in this study. While this criterion assured a manageable, measurable compilation of data to inform NCC, it also excluded the selection of options with higher relevance. Therefore, as institutions provide more data linked to the proxy variables identified

in this study, indicator selection may vary. Nonetheless, the 12 IF that these indicators aim to measure were developed considering international sources encompassing a global perspective and can be maintained.

2.4.2. Calling attention to priority areas and factors in SAMAs

Indicator values showed notable differences in NCC between the most populated SAMAs. While some areas like Santiago, Chile manage all domestic wastewater in state-of-the-art treatment systems and have implemented a national Circular Economy policy with clearly defined objectives and designated budget, other areas like Buenos Aires, Argentina treat just over 15% of their wastewater and have no similar policies in place. All areas showed both high and low relative indicator values, signaling that no area is leading or falling behind in all aspects of NCC. While the final aggregation of indicator values identified Montevideo, Uruguay as the area with the highest NCC and Asunción, Paraguay as the lowest in the region, it also indicated that most areas have relatively similar levels of overall NCC (Figure 4). Furthermore, some areas had contrasting levels of material and organizational NCC, like Santa Cruz de la Sierra, Bolivia with one of the highest scores of material capacity but also sharply low organizational capacity, while Sao Paulo, Brazil showed the opposite results.

The SAMA with the highest nutrient circularity capacity on both material and organizational levels coincides with having the highest GDP per capita in South America (World Bank 2021). This connection between this monetary indicator and nutrient circularity capacity may indicate that economic factors may be the greatest barrier for less wealthy countries like Paraguay and Bolivia. Nonetheless, there are areas with mid-level economic ranking that still reach higher levels of NCC, such as Bogotá, Colombia, and Quito, Ecuador. The elevated levels of NCC in these areas are not related to high levels of agricultural activity, but instead to higher levels of organic waste treatment. Overall, the combination of peri-urban agricultural activity, high investment in knowledge and innovation, and effective environmental management strategies have a strong impact on higher NCC levels in MAs.

Considering the administrative limits used for studied metropolitan areas, areas with less local arable land were destined to demonstrate low material capacity in indicators related to reutilization in agricultural activities. Since proximity and diversity of food production and consumption activities are vital to closing nutrient cycles, alternative geographic boundaries may increase these material capacity indicator values. On the other hand, organization capacity indicators are dependent on the priorities and capabilities of local institutions, which can be modified through local policies and can result in improvements in aspects like sanitation

infrastructure and waste management strategies, which will ultimately affect material flow capacity. Therefore, it may be more effective to prioritize increasing organizational capacity, since this is something that decision-makers can more directly modify and can indirectly result in increased total nutrient circularity capacity.

This assessment of factors influencing the transition to more circular nutrient management systems appears to be the first of its kind for South America, on both a national and metropolitan level. Overall, studies regarding sustainable transitions and nutrient circularity concepts for this area are rare, and though there is an increasing interest in circular economy research in the region, a key barrier to implementation is the lack of consensus regarding the principles and applicability of the concept (Betancourt Morales and Zartha Sossa 2020). These authors also highlight the need for a simplified conceptual framework than can be easily used by a variety of local stakeholders, while also considering the cultural and economic differences that exist between Europe, where this concept is heavily studied, and Latin America. The Circular Economy Coalition (2022) reports that Latin America and the Caribbean account for 14% of the world's food production, while wastewater treatment levels have been reported between 20-30%, and organic waste recovery is less than 1%. Aside from this research, multiple studies have identified Uruguay, Chile, and Colombia as regional pioneers in circular economy transition and waste management systems (Schröder et al. 2020; Bijos et al. 2022). Moreover, Schroder et al. highlight the importance of governmental support for research and innovation, as well as the prioritization of waste management and bioeconomy agendas in the Latin American context.

Data availability is not only deficient for academic transition and impact studies of circular nutrient systems, but also for local information databases regarding agricultural activity, material flow characteristics, resource recovery alternatives, and relevant institutional initiatives. Deductions using reference rates and equations were avoided in favor of locally reported quantities which were often difficult to find. Generally, waste management indicators in Latin America are limited by scarce, non-existent, or obsolete data, lack of transparency of information, and lack of homogeneity in the way this information is reported (Turcott Cervantes et al. 2018). In many cases, the data management necessary to inform these indicators simply does not exist in these areas, as is the case for the management of organic municipal solid waste. There are often isolated efforts from multiple initiatives in a city to promote composting, for example, but quantities are not recorded or shared among actors. With sludge treatment from wastewater treatment plants, this information exists but is not readily available or shared. Since increased research and innovation are linked to the transition to more circular nutrient

management systems, local actors and decision-makers must prioritize the generation and management of quality data to support such processes.

This SAMA NCC study provides a strong theoretical base and research inputs that can be used for future sustainability analyses. The selection of indicators can be used to understand a city or MA's ability to advance towards nutrient circularity, though local goals and characteristics, as well as stakeholder input, should be considered when assessing these values within the specific sustainable urban development process of an area. Setting specific benchmarks for each context was beyond the scope of this study. Instead, this SAMA assessment is meant to demonstrate how the interpretation and comparison of these results can help identify strengths and weaknesses, in this case in comparison to neighboring countries. Once these aspects have been identified, actors can deepen their local analysis and strategy development, possibly taking into consideration the strategies of their higher-scoring neighbors.

The NCC assessment allows for a broad assessment of a complex, multidimensional objective and aims to highlight areas of strengths and weaknesses in the studied region. This assessment did not aim to inform specific political interventions, strategies, or conclusions, nor should the improvement of one factor be considered capable of compensating for the low performance of another (Bracco et al. 2019). It is crucial to consider the conditions affecting each influencing factor individually when completing the necessary deeper analysis that these results aim to stimulate, thus avoiding simplistic or misleading policy conclusions.

2.5. Conclusion

Achieving sustainable management of nutrient-containing resources is vital to ensure reliable access to sufficient quantities of food. Though scientists and governments have been exploring strategies with this objective, these efforts and subsequent results have often been developed considering situations that cannot be applied in different, sometimes highly contrasting realities. The results of this study affirm that the transition to nutrient circularity requires the consideration of factors that range across a variety of dimensions and disciplines. Through a pragmatic yet comprehensive analysis of NCC, actors can use credible, representative, existing information to better understand their present conditions, steer further analysis and discussion in that direction, and co-develop evidence-based, contextualized strategic plans and policies for a more sustainable future. Furthermore, by building on the findings of this assessment, researchers and stakeholders can assess the specific characteristics that affect NCC in other contexts, contributing to a more global understanding of NCC.

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2.7. APPENDICES

A. Inventory of factors identified from literature

Central Themes	Influencing Factor	References
Knowledge & Metrics	1. Research & development in resource recovery, secondary raw materials, circular business models & synergy opportunities	(Araujo Galvão et al., 2018; Goodwin Brown et al., 2021; Gottinger et al., 2020; Hart et al., 2019; Obersteg et al., 2019; Patricio et al., 2018; Ritzén & Sandström, 2017a; Salmenperä et al., 2021; Tura et al., 2019; Vanhamäki et al., 2020; Williams, 2019)
	2. Relevant expertise, skills, competencies for circular resource management	(Farooque et al., 2019; Goodwin Brown et al., 2021; Gottinger et al., 2020; Hart et al., 2019; Houston et al., 2018a; Patricio et al., 2018; Ritzén & Sandström, 2017a; Salmenperä et al., 2021; Tura et al., 2019; Vanhamäki et al., 2020)
	3. Established metrics and standards for quality and safety control	(Araujo Galvão et al., 2018; de Mattos & de Albuquerque, 2018; Gottinger et al., 2020; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Vanhamäki et al., 2020; Williams, 2019)
	4. Information / Data availability	(Araujo Galvão et al., 2018; Bassi et al., 2021; Farooque et al., 2019; Goodwin Brown et al., 2021; Gottinger et al., 2020; Jarre et al., 2020; Obersteg et al., 2019; Patricio et al., 2018; Tura et al., 2019; van der Wiel et al., 2019; Williams, 2019)
Market & Economy	5. Costs of business transformation; Investments	(Araujo Galvão et al., 2018; Farooque et al., 2019; Gottinger et al., 2020; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Patricio et al., 2018; Salmenperä et al., 2021; Tura et al., 2019)
	6. Cost of virgin/finite/new resources	(Hart et al., 2019; Houston et al., 2018b; Salmenperä et al., 2021; Williams, 2019)
	7. Consumer preferences, awareness, and engagement	(Aceleanu et al., 2019; Araujo Galvão et al., 2018; Farooque et al., 2019; Gottinger et al., 2020; Govindan & Hasanagic, 2018; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Patel et al., 2021;

		Salmenperä et al., 2021; Tseng et al., 2019; Tura et al., 2019; Williams, 2019)
	8. Viability and stability of secondary-raw material / product market	(Araujo Galvão et al., 2018; Farooque et al., 2019; Gottinger et al., 2020; Houston et al., 2018b; Jarre et al., 2020; Patel et al., 2021; Patricio et al., 2018; Ritzén & Sandström, 2017b; Salmenperä et al., 2021; Tura et al., 2019; Vanhamäki et al., 2020)
Policy & Regulation	9. Political commitment & support	(Aceleanu et al., 2019; Araujo Galvão et al., 2018; Bassi et al., 2021; de Mattos & de Albuquerque, 2018; Gottinger et al., 2020; Houston et al., 2018b; Obersteg et al., 2019; Patel et al., 2021; Tura et al., 2019; van der Wiel et al., 2019; Vanhamäki et al., 2020; Williams, 2019)
	10. Environmental regulations	(Araujo Galvão et al., 2018; de Mattos & de Albuquerque, 2018; Farooque et al., 2019; Gottinger et al., 2020; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Salmenperä et al., 2021; Tseng et al., 2019; Tura et al., 2019; Vanhamäki et al., 2020; Williams, 2019)
	11. Financial support & incentives	(Goodwin Brown et al., 2021; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Salmenperä et al., 2021)
	12. Institutional Capacity & Transparency	(Houston et al., 2018b; Obersteg et al., 2019; Patel et al., 2021; Tura et al., 2019; Williams, 2019)
Sectoral Management & Cooperation	13. Corporate culture, vision, support, leadership, awareness	(Aceleanu et al., 2019; Araujo Galvão et al., 2018; Farooque et al., 2019; Gottinger et al., 2020; Hart et al., 2019; Obersteg et al., 2019; Patricio et al., 2018; Salmenperä et al., 2021; Tura et al., 2019; Williams, 2019)
	14. Cooperation/collaboration/communication throughout value chain / stakeholders	(Araujo Galvão et al., 2018; Bassi et al., 2021; Farooque et al., 2019; Goodwin Brown et al., 2021; Gottinger et al., 2020; Hart et al., 2019; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Patricio et al., 2018; Ritzén & Sandström, 2017b; Salmenperä et al., 2021; Tura et al., 2019; Vanhamäki et al., 2020)
	15. Business model and product design, practices, and innovation	(Araujo Galvão et al., 2018; Goodwin Brown et al., 2021; Gottinger et al., 2020; Govindan & Hasanagic, 2018; Hart et al., 2019; Houston et al., 2018b; Patricio et al., 2018; Ritzén & Sandström, 2017b; Salmenperä et al., 2021; Tura et al., 2019; van der Wiel et al., 2019; Vanhamäki et al., 2020; Williams, 2019)

Technology & Material Feasibility	16. Resource Agglomeration & Diversity	(Bassi et al., 2021; de Mattos & de Albuquerque, 2018; van der Wiel et al., 2019)
	17. Infrastructure capacity for collecting resources and supporting secondary-raw materials supply chains	(Bassi et al., 2021; Gottinger et al., 2020; Houston et al., 2018b; Jarre et al., 2020; Obersteg et al., 2019; Ritzén & Sandström, 2017b; Salmenperä et al., 2021; Tura et al., 2019)
	18. Technological capacity for recovering resources and processing secondary-raw materials	(Bassi et al., 2021; Farooque et al., 2019; Gottinger et al., 2020; Govindan & Hasanagic, 2018; Hart et al., 2019; Jarre et al., 2020; Obersteg et al., 2019; Patricio et al., 2018; Salmenperä et al., 2021; Tura et al., 2019)

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B. Indicator Appraisal Process

The following formulas were applied when assessing possible indicators. First, through an expert appraisal, feasibility and direct salience were scored.

Initial Indicator Appraisal (IIA):

Average Feasibility Score = Average [Max (Direct Indicator Availability, Raw Data Availability), Geo Scale, Recency]

Average Feasibility Score + Direct Salience Score = Initial Indicator Appraisal (IIA)

As mentioned previously, the identified influencing factors are not independent of each other, and often directly or indirectly influence one another in varying degrees. To acknowledge these relationships and avoid redundancy in the resulting selections, global salience was measured by considering the number of upstream and downstream connections between influencing factors, as shown in Figure 3, as well as the average feasibility score of each factor. To calculate the Global Salience Correction, a Weight was assigned to this variable (GSW). Three GSW were tested to compare 10, 50, and 100% importance concerning the IIA scores, resulting in GSW values of 0.1, 0.5, and 1.0 respectively.

Global Salience Correction:

Upstream Correction = +GSW × number of connected upstream IF with lower IIA Average
Downstream Correction = -GSW × number of connected downstream IF with equal or higher IIA Average
UC + DC = Global Salience Correction (GSC)

Then the *Initial Indicator Appraisal* and the *Global Salience Correction* were added together to determine the **Final Indicator Appraisal** for each indicator.

Initial Indicator Appraisal + Global Salience Correction = Final Indicator Appraisal (FIA)

Finally, the indicators were ranked from highest to lowest Final Indicator Appraisal scores for each GSW variation.

C. SAMA Material Capacity Indicator Value References

1. **SÃO PAULO**
   a. **Metropolitan Area Definition**: “Greater São Paulo” or “Região Metropolitana de São Paulo (RMSP)” with 39 municipalities including the capital, São Paulo.
   b. Data sources:
   - Instituto Brasileiro de Geografia e Estatística, Fundacao SEADE. *Perfil da Região Metropolitana de São Paulo.* https://www.emplasa.sp.gov.br/RMSP
   - MapBiomas. 2020. *Landcover for 39 muni of RMSP, Agriculture and Mix Pasture+Agri.* https://mapbiomas.org/en/statistics
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2. **BUENOS AIRES**
   a. **Metropolitan Area Definition:** Región Metropolitana de Buenos Aires (RMBA)
   b. Data sources:
   - Instituto Nacional de Estadística y Censos (INDEC). *Censo Nacional de Población, Hogares y Viviendas 2010*. https://observatorioamba.org/planes-y-proyectos/rmba#datos
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   - M. Ramirez, Treatment Plant Manager in AYSA, personal communication, December 9th, 2021.
3. **LIMA**
   a. **Metropolitan Area Definition:** Lima Province + Callao Province
   b. Data sources:
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   - Instituto Nacional de Estadística e Informática (INEI). *Censos Nacionales 2017: XII de Población, VII de Vivienda y III de Comunidades Indígenas*. http://censo2017.inei.gob.pe/resultados-definitivos-de-los-censos-nacionales-2017/

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4. **BOGOTÁ**
   a. **Metropolitan Area Definition:** Bogotá D.C; Soacha; Facatativa; Zipaquirá; Chía; Mosquera; Madrid; Funza; Cajicá; Sibaté; Tocancipá; La Calera; Sopó; Tabio; Tenjo; Cota; Gachancipá; Bojacá
   b. **Data sources**:
      - Departamento Administrativo Nacional de Estadística (DANE). 2021. *Evaluaciones Agropecuarias Municipales - Base agrícola 2019-2021 (EVA - UPRA).* https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=59
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5. **SANTIAGO**
   a. **Metropolitan Area Definition**: 52 Comunas of the Metropolitan Región
   b. **Data sources**:
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- S. Duran, Head of Biosolid Resources in Aguas Andinas, personal communication, 17 August 2022.

6. **QUITO**
   a. **Metropolitan Area Definition**: Distrito Metropolitano (Canton) de Quito with 9 "administrative zones"; 32 urban parishes and 33 rural and suburban parishes
   b. **Data sources**:
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D. Description of Influencing Factors

Central Theme	Influencing Factor	Component summary
1. Material Flow Potential	1.1 Agglomeration of nutrient subsystems	What kind of nutrient related activities exist in the area, and how close/connected are they to each other? When assessing this factor, spatial characteristics are key, such as distribution, concentration and surface area. This also considers the diversity of nutrient-related activities, as well as proximities between them.
	1.2 Nutrient Flow Quality and Quantity	What nutrient-containing flows are available in the region and what characteristics do they have? How much is separated and collected for posterior reuse or treatment? Characteristics of waste flows, such as composition, quality, and quantity, considering characteristics of population, productive activities, and recovery activities. Infrastructure and management of waste flows is also assessed, including separation and collection rates.
	1.3 Flow Treatment and Recovery Options	What kind of treatment options exist for nutrient-related waste flows, and how much of the recovered products are or can be reincorporated into food and feed value chain (from technical & infrastructural point of view)? Technological availability &

Central Theme	Influencing Factor	Component summary
		capacity (feasibility) for recovering resources from waste flows and processing secondary-raw materials
2. Food & Feed Value Chain Characteristics	2.1 Consumer Behavior	What values, goals and practices reflect the local population? Existing consumer values, norms, and habits are considered, as well as the acceptance and demand of recovered materials/products. This also relates to the pressure that drives business transformation and support market development.
	2.2 Stakeholder Cooperation	How much communication and collaboration occurs between different actors of the value chains? This includes the existence of spaces for stakeholder collaboration, such as cooperatives, coalitions, or online material exchange platforms.
	2.3 Secondary Material Market Development	How (economically, logistically, productively?) feasible is it for different actors of the value chain to transition to circular models, designs, and practices? Financial determinants are considered, such as costs and stability of input materials, as well as production capacity. Furthermore, the viability and stability of secondary raw material supply chain are considered.
	2.4 Business Culture and Practices	What values, goals and practices reflect the actors/businesses along the value chains? How linear (or circular) are current business models, product designs, and production practices within different actors of the food & feed value chains? Values and practices of actors along the value chain, such as company culture, vision, and transparency. This also considers the drive (or aversion) to invest in innovation or to improve sustainability. Another aspect to consider is the amount of (“green”) entrepreneurship in the area.
3. Knowledge Base	3.1 Available information and expertise	How much relevant data is available from and between different actors? Is this information available to stakeholders? How many experts in resource recovery / circular resource management are available for the necessary roles to aid transition (business transformation, research, government)? Is training available? This factor considers: a) Possibility of collecting, processing, and sharing relevant, detailed, reputable information on the necessary scales and dimensions and b) Availability of professionals in relevant fields, such as circular business models, resource treatment and recovery, as well as the opportunities to train in such fields.
	3.2 Research and Development	How much effort and resources are being dedicated to research and development of business transformation and resource recovery & reuse? This factor is divided into two main aspects: a) Investigation of business transformation, including the existence of pilot projects or circular business models, as well as the tools and metrics to measure their financial benefits. The development of stakeholder collaboration and knowledge exchange tools and platforms is also considered. b) Research & development into resource recovery and processing of secondary raw materials. This

Central Theme	Influencing Factor	Component summary
		especially concerns information necessary to establish metrics and standards for environmental, safety and quality control.
4. Institutional Support	4.1 Political and Financial Support	What policies represent the commitment of the local, regional, and national government to resource recovery (specifically, nutrient circularity), and how are they monitored? How are institutions financially supporting transitions to nutrient circularity? Political commitment can be assessed through the existence of regional, national, and local policies that supports reduction of food waste, the increase in recovery and revalorization of nutrients, and general policies that support bioeconomy and circular economy agendas. This includes national or local road maps, action plans, clear goals and targets, and indicator reporting systems. It is important to consider how these commitments and policies compare to other political priorities. Financial support includes public funds available to support business transformation, innovation initiatives, for relevant research, and for campaigns to raise awareness and share/promote information. This factor also considers tax incentives, such as subsidies for sustainable practices.
	4.2 Institutional Capacity	How prepared and capable are institutional actors to support transitions to nutrient circularity? The assessment of this factor should consider the region's institutional capacity to establish regulations and monitor them, to manage data on different scales, to enable collaborations within and between sectors, and to communicate effectively with stakeholders. This factor also considers the level of corruption and/or transparency of institutions.
	4.3 Environmental Standards and Regulations	Is there a supportive regulatory framework in place to support transitions to nutrient circularity? Supportive environmental regulations can include business and production regulations, such as an Extended Producer Responsibility law, regulations on the import, extraction and use of finite/virgin resources, criteria in public procurement, waste management control, among others. This factor also includes quality and safety standards & certification for secondary materials, such as organic fertilizers, compost, etc.

E. Threshold Values for SAMA Assessment

Indicator	Thresholds	
	Low	High
1. Hectares of crop production in MA per capita	<.01	>.05
2. Monogastric livestock heads per capita	<.01	>.05
3. Percentage of organic solid waste that is collected separately	<.01%	>1%

4.	Percentage of discharged wastewater that receives (at least) secondary treatment	<20%	>50%
5.	Percentage of sludge waste that is treated for nutrient recovery	<10%	>50%
6.	GII: 5.2 Innovation Linkages	< 16.5	> 30.5
7.	National Spatial Data Infrastructure Development Index (CEPAL STAT)	< 24	> 35
8.	GII: 6.1 Knowledge Creation	< 6.15	> 30.43
9.	Percentage of TSE dedicated to GSSEA	< 0.42%	> 11.29%
10.	Existence of National Circular Economy Policy	No	Yes

1. For metropolitan areas as defined in this study (see Section 2.1.3), values of less than 100 m2/capita, resulting either from their extensive urbanization or their arid or mountainous setting, structurally designate MAs of low nutrient demand. Only intensively cropped MAs with a flat topography exceed a value of 500 m2/capita. This leaves a middle range of MAs with significant cropping, but constrained by limitations that cannot be overcome.

2. Monogastric livestock can be near absent from MAs. Choosing a threshold of 1 tropical livestock unit per 100 inhabitants, equating 1 pig per 25 inhabitants, allowed MAs known to exhibit little or no industrial monogastric production to be considered as low. Conversely, a threshold of 5 tropical livestock units per 100 inhabitants allowed to consider only MAs known to exhibit large, intensive peri-urban livestock operations as high.

3. In any MA the share of organic solid waste that is collected separately is, at that scale, low. But organic solid waste is well known to be a very large material flow in any MA. Even low shares of collection may therefore make for significant initiatives, while "larger than insignificant" shares also testify of a political openness for similar future initiatives. We chose little sensitive high and low thresholds two orders of magnitude apart, clearly distinguishing "substantial separate collection" MAs from MAs with no or insignificant separate collection, while allowing for a substantial middle ground of less unambiguous status.

4. MA sewage treatment varies widely at the level of Latin America and globally. As a result, MAs are found throughout the entire 0 - 100% secondary treatment range. We tentatively and rather arbitrarily considered MAs where a majority of sewage receives secondary treatment as high and those where less than one fifth receives such treatment as low.

5. Similar to the above, but a large share of MAs is known to practice no such treatment at all. We thus lowered the "low" threshold to one tenth in order to allow for a larger middle ground range. Still, this is the only indicator where no MA from our sample ended up in this intermediate class.

6-9 For organizational capacity indicators, since these were already existing indicators, we considered the full range of values from their respective datasets to determine thresholds. In order to take into account, the distribution of the values, we used box plot graphs to determine low (Quartile 1), medium (Quartile 2-3), and high (Quartile 4) categories for each indicator.

10. Since this indicator was based on one of two possible descriptive answers, only “high” and “low” categories were assigned.

The next step towards planning nutrient-circular cities and regions is to determine how a specific city or region can conduct a comprehensive, planning-oriented assessment of these factors. This initial phase of the planning process requires the integration of urban metabolism and urban planning principles and tools to address the multiple dimensions influencing resource management. The analyses used in this assessment must process diverse types of information within these dimensions and evaluate the factors in relation to the systemic and circular principles of nutrient circularity. The resulting diagnostic should produce findings that are valuable for planning processes by highlighting key opportunities and challenges that must be considered when developing strategies.

Note: This article has been peer reviewed and is under revision for publication in the Journal of Cleaner Production.

3. **SPACE, FLOWS, & PEOPLE:** A STRATEGIC, MULTIDIMENSIONAL DIAGNOSIS OF NUTRIENT FLOW MANAGEMENT IN THE METROPOLITAN REGION OF SANTIAGO

3.1. Introduction

Large cities and their surrounding metropolitan areas are known for their concentration of myriad resources, including energy, water, infrastructure, and human capital. These territories contain vital functions related to economic exchange, industrial production, innovation, etc., with a constant flux of resources (Medeiros and van der Zwet 2020). All around the world, cities and their metropolitan areas are growing through rapid and often unorganized urbanization processes that take place within a primarily linear economic system and are accompanied by concerns over resource availability and environmental degradation (Da Gama Torres 2011). This is especially true for countries in the global south, which are experiencing the highest urban population growth in recent years (World Bank 2018). Cities in South America and other regions of the Global South are currently engaged in strategic planning processes aimed at integrating sustainability principles, such as the Sustainable Development Goals (SDGs), into their urban policies and roadmaps (Metson et al. 2022).

In this context, food security is a top priority, especially regarding climate change adaptation. Agriculture is a major contributor to the transgression of planetary boundaries, driving four of the five boundaries in high or increasing risk zones and significantly impacting others that remain within safe limits (Campbell et al. 2017), largely due to the excessive and resource-intensive use of nutrient inputs. Meanwhile, urban areas are grappling with increasingly complex waste management issues, particularly the challenge of sustainably managing large organic waste streams generated within cities. To mitigate the adverse impacts of open, linear agri-food-waste systems, nutrient circularity strategies are being investigated. These strategies aim to reduce mineral extraction for fertilizers, optimize the recovery of byproducts and waste for reintegration into productive systems, and minimize nutrient losses and environmental pollution. However, the practical implementation of these strategies is slow, particularly in South American city-regions, where there is high dependence on imported fertilizers, while most organic municipal solid waste is disposed of in landfills or open dumps, and wastewater collection and treatment systems are insufficient (Circular Economy Coalition 2022).

Researchers and practitioners continue to face challenges in developing strategies to effectively close or improve nutrient cycles in real-world contexts. Transitioning to sustainable nutrient management requires systemic change and comprehensive strategic planning (Medeiros and van der Zwet 2020). Strategic urban planning involves a systematic approach to development, emphasizing the prioritization of key issues through consensus and thorough analysis (UN Habitat 2007). The initial assessment phase, which concludes with a diagnosis, is critical for strategy formulation, particularly when addressing nutrient circularity, which encompasses diverse types of information and multiple factors influencing these systems (Arciniegas et al.; UN Habitat 2007). However, conducting such analyses on a practical, territorial scale remains

a significant challenge. This study focuses on how cities and regions can acquire the necessary information to develop effective systemic nutrient circularity strategies.

To address this, two key domains of research intersect: urban metabolism and urban planning. As is further described in the next section, both fields offer distinct frameworks, tools, and strategies aimed at fostering sustainable territorial development, yet they often operate in isolation. Moreover, translating and integrating findings into accessible and actionable information remains challenging (Jedelhauser and Binder 2018; Yetano Roche et al. 2014). As a result, institutions and decision-makers often lack the critical insights necessary for developing comprehensive and effective plans and policies. Furthermore, the advancements and applications of nutrient circularity research with urban metabolism or urban planning tools are primarily concentrated in Europe, with limited contextualized information available for regions like South America, where urbanization rates are among the highest in the world, presenting both significant challenges and opportunities in terms of mitigation and adaptation strategies.

Effective and sustainable nutrient circularity strategies require access to strategic yet comprehensive information. This research aims to address this gap by integrating existing concepts and methodologies from the fields of urban metabolism and urban planning, combining spatial, material flow and stakeholder analyses inputs, to develop a strategic and comprehensive territorial diagnosis of nutrient flow management. The applicability and relevance of these frameworks to urban planning processes is central, while also promoting a systemic and circular approach to managing nutrient-containing flows. This approach was applied to the Metropolitan Region of Santiago, an area undergoing significant planning processes relevant to circular resource management. As a regional forerunner in nutrient circularity capacity, Santiago de Chile serves as a representative case study for other urban areas facing similar challenges (Fleitas Girett et al. 2023).

3.2. Theoretical Framework

Urbanization exacerbates environmental and socioeconomic challenges, particularly those related to infrastructure, housing, food security, and resource management. The goal of sustainable urban development is to create cities that benefit both people and the environment (Wheeler 1996). This concept is commonly associated with the social, environmental, and economic dimensions of development and is recognized as a complex interplay of factors and processes that necessitates analysis from diverse perspectives and disciplines. Two critical disciplines for achieving sustainable urban environments are urban metabolism and urban planning. These interdisciplinary fields are inherently linked, both aiming to develop systemic strategies for sustainability and resilience across various territorial scales, although their methodologies and areas of focus differ.

Urban metabolism quantifies and examines resource flows within and between urban and regional boundaries, characterizing subsystems in terms of input and output flows to identify opportunities for increased resource efficiency. Urban planning, traditionally associated with engineers, architects, and planners, emphasizes effective land use, infrastructure development, and the enhancement of residents' quality of life, often with a long-term perspective (Calthorpe 1993; Morenas et al. 2013). In recent years, the circular economy has emerged as a prominent theory for minimizing resource use within the context of urban sustainability. This model of production and consumption seeks to reduce resource demand by optimizing product design, processes, business models, and supply chains through dematerialization and strategies for closing resource loops (Childers et al. 2011; Valve et al. 2020; Vanhamäki et al. 2020; Stegmann et al. 2020).

The circular economy framework distinguishes between technical and biological cycles, with the latter focused on closing renewable resource loops. This involves analyzing the interconnections between food and urban systems and recognizing the critical relationship between organic residues generated in cities and the nutrient needs of agriculture (Metson et al. 2022; van der Wiel et al. 2019). Achieving nutrient circularity requires spatial, multi-actor, and quantitative considerations to link rural agricultural demands with urban organic outputs effectively. The following sections will examine how urban metabolism and urban planning principles and tools can be integrated to advance nutrient circularity in urban contexts.

3.2.1. Urban Metabolism

Understanding material flows is fundamental to achieving sustainable development goals, such as sustainable resource management and urban resilience. The concept of urban metabolism (UM) was first introduced by Abel Wolman in 1965, likening the city to a “living organism” with material and energy inputs, stocks, and outputs. Wolman's work inspired further research, and UM has since evolved to encompass the study of “the sum of technical and socioeconomic processes within cities,” analyzing resource inflows, outflows, and accumulation within a given territory (Derrible et al. 2021; Kennedy et al. 2011). Urban metabolism research illustrates how material flows are interconnected with broader socioeconomic systems, often extending beyond city or regional boundaries. By identifying these connections, suggesting infrastructure redesign, and highlighting opportunities for resource recovery, UM studies provide critical insights for urban policy and strategic planning (Lucertini and Musco 2020).

Early UM studies, such as those on Brussels by (Duvigneaud, P., Denaeyer-De Smet, S. 1977) and Hong Kong by (Newcombe 1977), laid the groundwork for more comprehensive analyses. Over the past few decades, numerous cities across Asia, North America, and Europe have undergone structured mass flow assessments. These studies, motivated by varying policy

objectives and target substances, generally aim to identify priority sectors for intervention, optimizing resource allocation (Sahely et al. 2003; González et al. 2013; D'Amico et al. 2022; Niza et al. 2009; Chen and Chen 2012).

Material Flow Analysis (MFA) remains the most widely employed tool in UM research. It models the mass balances of materials and energy stocks within a defined territory, prized for its simplicity and adaptability (Allesch and Brunner 2015; Hoekman and Bellstedt 2020). UM research has used MFA in various approaches, such as territorial and supply-chain models for infrastructure planning (Guibrunet and Sánchez Jiménez 2023), and goods-level studies to facilitate stakeholder collaboration (Yetano Roche et al. 2014). Sectoral analyses have been conducted to distinguish material demands and environmental impacts (Wang et al. 2020b), while some studies use MFA to examine the evolution of material and energy flows over time, inferring the influence of behavioral and lifestyle changes stemming from the circular economy (Papageorgiou et al. 2024). The versatility of MFA enables researchers to define system boundaries, select processes, and optimize different flow types, yielding insights into economic and environmental impacts (Céspedes Restrepo and Morales-Pinzón 2018; Kraker et al. 2019).

In addition to MFA, various indicator frameworks are employed to synthesize UM findings and align them with research objectives. Widely adopted indicators, such as the ecological footprint and life-cycle assessment metrics, distill complex information into actionable insights (Lucertini and Musco, 2020). Sankey diagrams are another popular tool in UM studies, visually representing material flows within a specific functional unit or time period, with the width of the flow lines corresponding to their magnitude (Lupton and Allwood 2017).

Despite its strengths, UM research has faced criticism for its tendency to operate as a "black box," often overlooking the spatial, environmental, and socioeconomic complexities of urban flows (Beloin-Saint-Pierre et al. 2017; Hoekman and Bellstedt 2020; Perrotti 2020). Recent efforts have aimed to address these limitations by integrating flow processes with network models, facilitating a deeper understanding of internal mechanisms and subsystem interactions (Zhang et al. 2015). Data availability and quality remain significant challenges for UM studies. Data aggregation is often difficult, leading to compromises such as relying on national data instead of local information or using outdated conversion coefficients from unrelated studies, which may not accurately reflect local conditions (Restrepo and Morales, 2018; Guibrunet et al., 2023).

3.2.2. Urban Planning

Metropolitan areas and regions often exhibit significant spatial variation, characterized by diverse land uses and activities that contribute to the stability and dynamics of urban systems (Cumming 2011). However, urban expansion, particularly in the Global South, is frequently

marked by unplanned and haphazard development (Burdett, R., Kaasa, A 2011; Rojas et al. 2013). This kind of growth negatively impacts spatial diversity, especially in peri-urban and rural areas, by increasing land costs, reducing agricultural activity, and limiting the development of industrial and waste treatment facilities (Surya et al. 2021; Wang et al. 2020a). Addressing these complex and interconnected challenges has become a key focus for researchers and urban planners committed to advancing sustainable urban and territorial development. The United Nations Sustainable Development Goals (SDGs) encompass these concerns, and countries worldwide have committed to not only achieving these goals but also integrating them into their territorial planning processes.

Urban planning frameworks and tools are designed to improve the planning, design, and development of cities and territories by promoting sustainability, reducing inequalities, fostering resilience, and enhancing quality of life (United Nations 2017). As an interdisciplinary field, urban planning requires multi-level governance and inter-sectoral collaboration, engaging stakeholders across various territorial levels (Ferry et al. 2018; Medeiros and van der Zwet 2020). Traditionally, these challenges have been approached with a focus on infrastructure and social aspects, led mainly by architects and geographers (Calthorpe 1993; Morenas et al. 2013). As highlighted by the UN's guideline on "Inclusive and Sustainable Urban Planning," urban planning processes should also be multidimensional, dynamic, and participatory (UN Habitat 2007).

Unlike conventional urban planning methods, strategic urban planning is selective, action-oriented, and focused. The Canadian Urban Institute (2001) outlines strategic planning as addressing three core questions: 1) Where are we currently?, 2) Where do we want to go?, and 3) How do we get there? The first question requires a thorough urban diagnosis, including an analysis of physical, environmental, and socioeconomic conditions, and the identification of key stakeholders. This diagnosis often employs geographic information systems (GIS) for spatial analysis, revealing trends and forming the foundation for strategic coordination across different territorial and sectoral groups (Ek and Santamaria 2009). Addressing this initial question is critical before moving on to the “planning” and “implementing” phases. Environmental considerations within urban planning are often addressed through infrastructure, green spaces, connectivity, and climate change adaptation. Additionally, local stakeholder engagement, through interviews, surveys, and workshops, plays a crucial role in enriching the analysis and planning processes. The insights gained are often visualized through models or maps, which are used to communicate with stakeholders and explore potential future strategies and impacts.

The United Nations' "Our City Plans Toolbox" was developed to guide urban planners in a dynamic and inclusive approach to sustainable urban development, encompassing analysis, planning, and implementation phases (UN Habitat 2022). According to this framework, the initial

assessment phase concludes with a comprehensive diagnosis that informs future planning efforts. This diagnostic process not only describes the current context but also identifies barriers and opportunities aligned with predetermined objectives. It combines desk and field research conducted by a technical team, and when led by urban planners, the findings are validated through a workshop with an advisory committee. This research applies the same diagnostic-building approach, focusing specifically on nutrient circularity within the urban context.

3.2.3. Nutrient Circularity

Nutrient circularity goes beyond the mere recycling of organic waste; it encompasses waste prevention and the strategic integration of bio-based materials within a circular economy framework (Annevelink and Harmsen 2010; Annevelink et al. 2017). This concept aligns closely with urban food flow and organic waste analysis, aiming to link these systems to facilitate the closing of nutrient loops. Moreover, nutrient circularity intersects with multiple United Nations Sustainable Development Goals (SDGs), including Zero Hunger, Clean Water and Sanitation, Sustainable Cities and Communities, Responsible Consumption and Production, and Climate Action (Metson et al. 2022).

Van der Wiel et al. (2019) conducted a comprehensive review of existing nutrient circularity studies, noting that many focus on nutrient surplus zones, use administrative boundaries, emphasize phosphorus and nitrogen, consider static one-year periods, and commonly apply Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) methods. Their research advocates for a more holistic approach, incorporating five key subsystems—Crop Production (CP), Animal Production (AP), Food & Feed Processing (FP), Commerce & Consumption (CC), and Waste Treatment & Recycling (TR)—and analyzing multiple macronutrients to gain a comprehensive understanding of regional agri-food-waste systems (Figure 1).

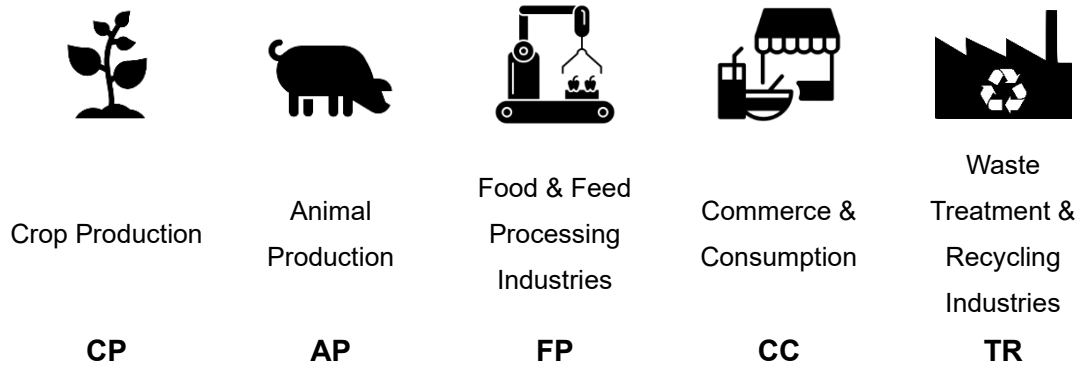

Figure 1. Subsystems of agri-food-waste systems to be included in the analysis of regional nutrient circularity, with their respective abbreviations as used in this article, based on van der Wiel et al. (2019)

Social and economic factors impacting agri-food-waste systems have also been extensively examined, prompting the integration of institutional and stakeholder perspectives. Bijon et al.

(2023) proposed a classification of actor roles, distinguishing between material and influential actors. Material roles include Producers, Collectors, Transformers, and Users, while influential roles encompass Planners/Administrators, Articulators/Coordinators, Promoters/Advisors, and Regulators/Enforcers (Figure 2).





Material Actor Roles:	**Influential Actor Roles**:
Producer	Plan / Administrate
Collector	Articulate / Coordinate
Transformer	Promote / Advise
User	Regulate / Enforce

Figure 2. Actor role classification for the analysis of regional nutrient circularity, adapted from Bijon et al. (2021).

To assess nutrient circularity, various indicators have been proposed. Forkes (2007) developed a nitrogen balance model for Toronto, analyzing the impact of municipal waste management policies on nitrogen recovery and recycling. Kraker et al. (2019) used the Urban Harvest Approach, employing indices like self-sufficiency, resource export, and waste output to evaluate desirability of household nutrient production and recycling scenarios at a district level in Santiago de Chile. Papangelou and Mathijs (2021) measured phosphorus circularity in Brussels, illustrating the outcomes of transforming the city's linear system into more circular food scenarios. Harder et al. (2021) examined nutrient flows in Canadian bioregional food systems, recommending circularity indicators to inform nutrient management policies.

These studies predominantly emphasize material and technical resource efficiency, employing urban metabolism methodologies to provide quantitative data. However, their potential impact on urban planning could be greatly enhanced by considering the spatial, institutional, and societal complexities inherent in urban systems (Loiseau et al. 2012; Perrotti 2020; Oliveira and Vaz 2021; Velasco-Muñoz et al. 2021).

3.2.4. Integrating towards a strategic diagnostic framework

Bridging the divide between urban metabolism and urban planning is crucial for advancing nutrient circularity in cities. The integration of these approaches offers significant opportunities and benefits, combining their respective strengths to create more effective and actionable frameworks. Urban metabolism research typically provides extensive, quantitative, and theoretical insights. However, these findings often lack the political and economic context

needed for practical application, making it challenging to translate them into concrete policies and nutrient management strategies (Perrotti, 2020; Oliveira and Vaz, 2021). Additionally, urban metabolism studies frequently overlook the spatial and social dimensions that are vital for urban planning processes (Lucertini and Musco, 2020). Conversely, urban planning emphasizes spatial analysis and incorporates economic and social considerations but often neglects environmental and circularity aspects related to material flows (Kotsila et al. 2023). Furthermore, planning frameworks are sometimes constrained by outdated or incomplete data, which can impede the formulation of effective and forward-thinking strategies. Integrating the comprehensive analytical capabilities of urban metabolism with the contextual and spatial expertise of urban planning can therefore address these limitations, promoting a holistic and strategic approach to urban nutrient management.

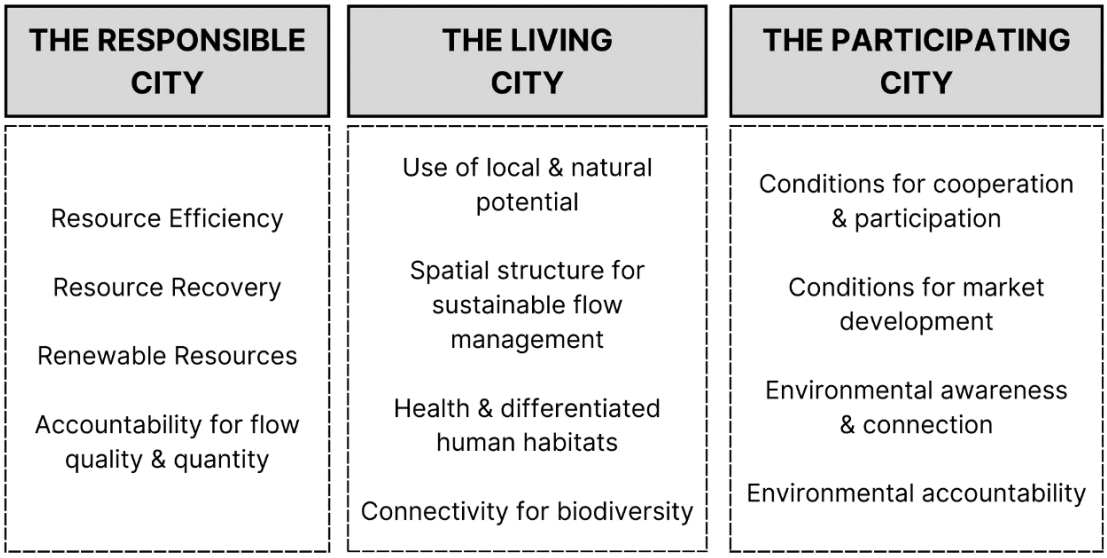

Figure 3. Adaptation of the guiding principles of the Ecopolis Strategy Framework (Tjallingii 1995)

Recognizing the shared goal of sustainable urban and territorial development, researchers have proposed integrated frameworks that combine essential concepts and tools from urban metabolism and urban planning. The pioneering work of Tjallingii (1995), the “Ecopolis Strategy Framework” (later termed the “Ecological Conditions Strategy”), introduced a planning tool focused on responsible resource flows, livable spaces, and active stakeholder participation (Figure 3). This framework organized flow data into spatial levels, helping to clarify flow management dynamics and identify key drivers and barriers. It also highlighted the risks posed by the openness of territorial systems, emphasizing concerns related to increased material inputs and outputs, spatial diversity loss, and the emergence of “source and sink” problems (Tjallingii 1996). Tsui et al. (2022) expanded on the Ecopolis framework, underscoring the integration of spatial, material, and social analyses for urban sustainability strategies.

Loiseau et al. (2012) advocated for urban metabolism (UM) research to offer stakeholders actionable insights for public policy development, particularly in territorial planning. Hoekman and Bellstedt (2020) supported this, noting that many UM studies are explicitly designed to inform urban planning, indicating a trend toward evidence-based urban sustainability strategies. Recent studies have sought to merge urban metabolism and urban planning tools to address circularity challenges. For example, (Viva et al. 2020) introduced "multi-pillar mapping," which integrates Material Flow Analysis (MFA), Sankey diagrams, GIS mapping, and social analysis for systemic waste management strategies. The REPAiR project developed an Activity-based Spatial MFA, linking material flows with actors and economic activities (Geldermans et al. 2019). In nutrient circularity research, Jedelhauser and Binder (2018) emphasized the necessity of spatial analysis, highlighting the need for varied scales to assess components ranging from households (local) to agriculture (regional) and the fertilizer industry (national/international). Regional analyses by Papangelou and Mathijs (2021) and Harder et al. (2021a) have also focused on linking nutrient flows to agri-food systems and developing circularity indicators. Furthermore, recent UM studies have integrated non-accounting methodologies, such as agent-based modeling, scenario analysis, and typology development, to provide a more systemic vision (Hoekman and Bellstedt, 2020).

These approaches enable researchers to examine complex interdependencies within urban systems, crucial for pinpointing priority areas for intervention and crafting effective nutrient circularity strategies. Figure 4 presents an overview of the principles, concepts, methodologies, analytical tools, and contextual factors from the theoretical framework, integrated into the diagnostic framework to enhance nutrient circularity through strategic regional planning.

3.3. METHODOLOGY

The primary goal of this research was to produce a diagnostic of nutrient flow management that is both strategic and multi-dimensional, able to inform local urban planning processes. Through this diagnostic, we aim to deliver crucial, selective, contextualized information (*strategic*) based on the assessment of real, current data connected to the diverse material and socioeconomic factors (*multidimensional)* that affect nutrient flow management.

The methodology developed in this study provides a comprehensive framework for integrating various tools to analyze regional nutrient-flow management and promote circularity. As shown in Figure 4, the approach combines urban metabolism methods for quantitative flow analysis with urban planning techniques that focus on stakeholder engagement and analysis as well as GIS-based spatial analysis. Guided by principles of sustainability, resilience, and circularity, this approach includes nutrient flows from agricultural, food, and waste subsystems, providing the multi-dimensional analysis needed for effective nutrient management.

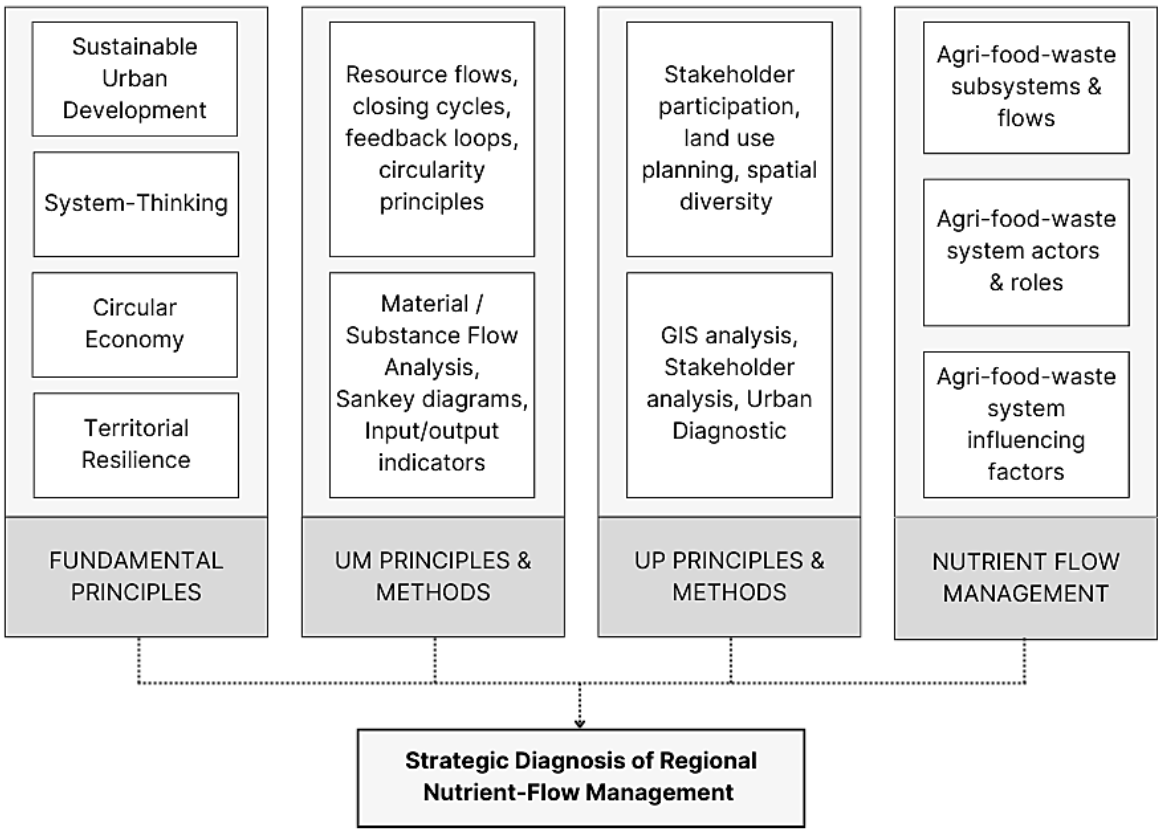

Figure 4. Integration of key principles, concepts and methods from urban metabolism (UM), urban planning (UP) and nutrient-flow management research applied in this study.

The overall framework expands upon the broad guidelines of the 'Our City Plans' toolbox from the UN framework, specifically Phase 1: Assessment, Block D, Analysis and Diagnosis' (see Appendix A). While the original framework provides general instructions for creating an urban diagnosis, this research refines and extends these guidelines by incorporating targeted principles and tools from urban metabolism and urban planning for assessing nutrient-flow management. Additionally, it builds on prior research that identified 12 influencing factors across four central themes impacting nutrient circularity capacity (NCC) from a territorial perspective. Using this foundation, the study organizes structured interviews, overall assessment, and result interpretation around these four themes: material flow potential, value chain characteristics, knowledge base, and institutional support (Fleitas Girett et al. 2023).

The analytical scope was explicitly designed to reflect the multidimensional characteristics of nutrient flow systems, incorporating agri-food-waste subsystems, actor roles, NCC influencing factors, and circularity objectives. The framework systematically integrates spatial, material flow, and social data using tools and principles from diverse disciplines. This interdisciplinary approach ensures a comprehensive understanding of nutrient flows while addressing the

interconnections between environmental, social, and economic factors critical for strategic urban planning/ The following subsections provide a detailed description of the steps involved in the analysis Figure 5. First, the strategic scope of the analysis is defined. Next, spatial, material, and social analyses are conducted. Finally, the information is synthesized into relevant diagnostic conclusions and summarized into two key indicators.

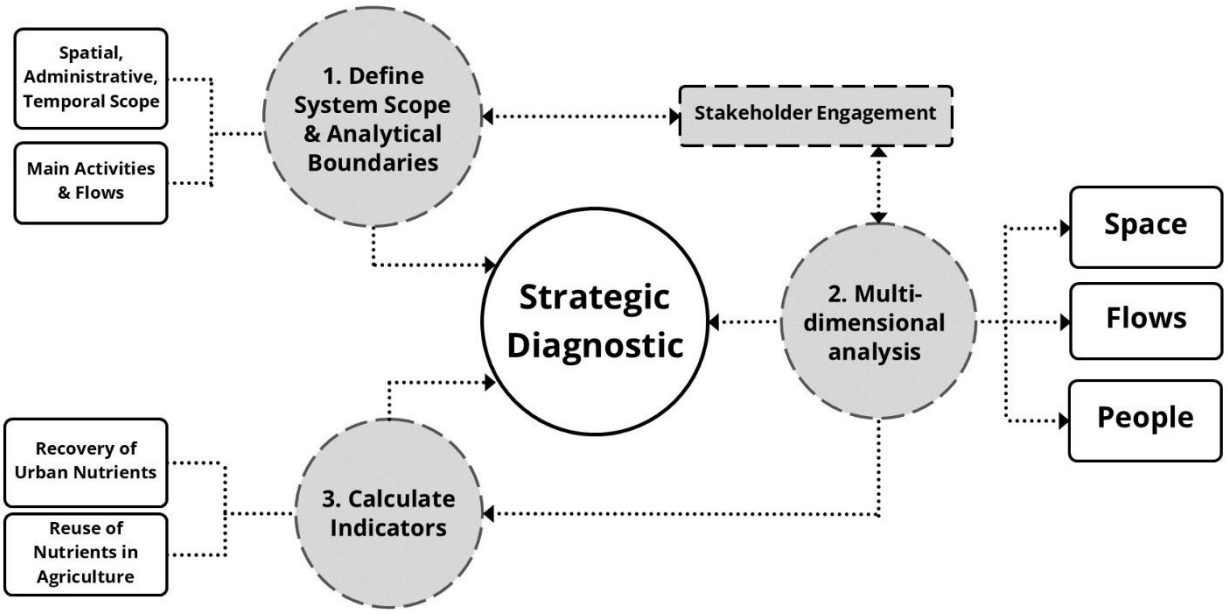

Figure 5. Summary of the proposed regional nutrient circularity diagnostic framework

3.3.1. Strategic Scope

Establishing appropriate scopes and boundaries is crucial for achieving strategic outcomes in planning processes. The scope definition must: a) reflect the unique characteristics of local practices and principles, and b) select detailed yet practical scales for analyzing various flow aspects (Olivera and Vaz, 2021). In this study, the scope encompasses all five subsystems of the agri-food-waste system and covers a sufficiently representative time period, as outlined by van der Wiel et al. (2019). This requires an initial review of regional agri-food system characteristics and data availability, along with consideration of the intended application of the research findings.

Data collection is conducted at the metropolitan area scale to align with the effectiveness of urban planning instruments and ensure the inclusion of all or multiple agri-food-waste subsystems. Meanwhile, data processing and outputs are structured at the subsystem activity level to generate precise, actionable insights. This design allows for linking outputs directly to

specific actors and policies, bridging the gap between system-wide interconnections and localized planning needs.

The framework employs a selective approach to data selection, focusing on flows that present the most critical challenges or opportunities for achieving nutrient circularity objectives while aligning with local priorities (Figure 6). To enhance clarity and relevance, flows are categorized into three strategic types: “Detrimental” flows: Nutrient losses or external imports that negatively impact circularity; “Opportunity” flows: Recovered or reused flows with high potential for optimization or expansion to improve system performance; and “Wellbeing” flows: Flows that currently support socioeconomic wellbeing, and are thus less immediately critical for urban planning interventions, such as the import of food for human consumption. By adopting this targeted focus, the framework minimizes unnecessary complexity while ensuring outputs remain directly relevant to the priorities of local systems and stakeholders.

This classification is adaptable and may evolve with political or economic changes, and it should be anchored in policy documents and validated through stakeholder engagement. This step strategically refines the scope, facilitating more effective processing of local data on activities and flows. To ensure a planning-oriented focus, the subsequent analysis focuses on 'detrimental' and 'opportunity' flows, which mainly involve nutrient losses, recovery, and reuse, while 'essential' flows are reserved for future iterations as circularity advances.

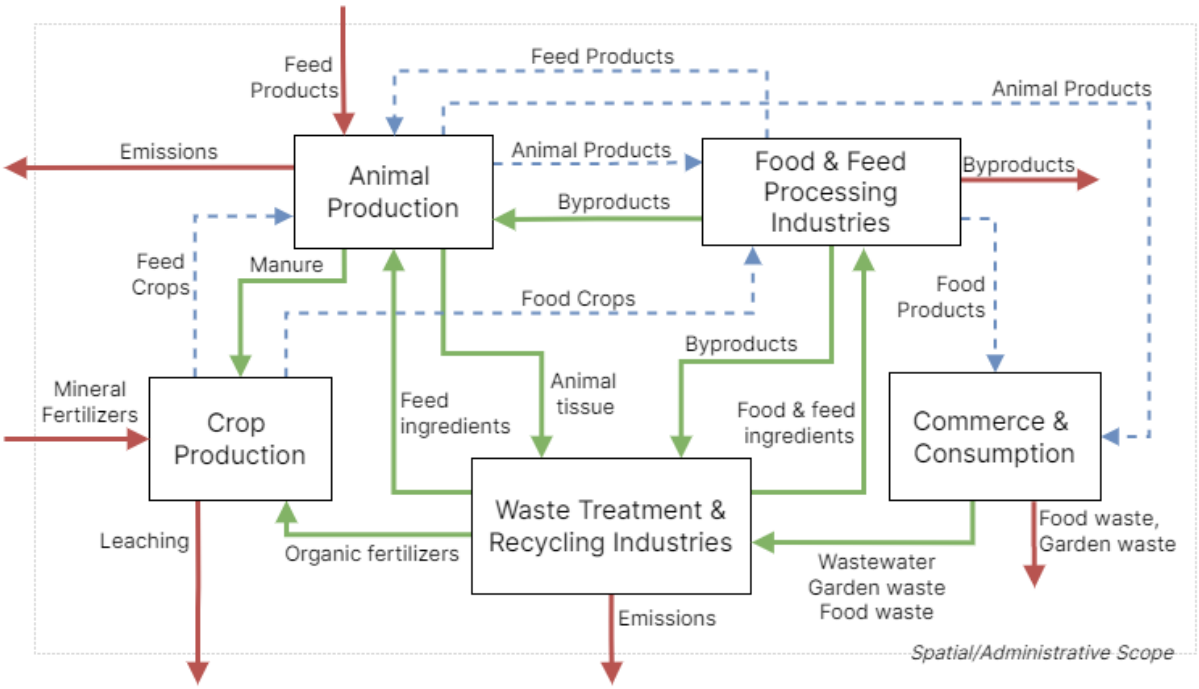

Figure 6. General classification system of flows applied in this research: blue dashed flows represent essential flows, red flows represent detrimental flows, and green flows represent opportunity flows.

3.3.2. Multi-dimensional Analysis

Multiple studies have determined that territorial, accounting type analyses to understand the flows of a studied area are the most suitable for future policy and spatial strategy development (Tjallingii 1996; Yetano Roche et al. 2014). In this research, the term multi-dimensional refers to three dimensions identified in the Ecopolis framework (Tjallingii, 1995): a material dimension composed of the associated nutrient-containing flows, a spatial dimension based on the studied territory and it's agri-food-waste system activities, and a social dimension that considers relevant actors and their roles, concerns, and interactions (Figure 7). This analytical approach is designed to be incremental, with each layer of analysis building sequentially on the previous one, rather than being developed separately and integrated later. The material, spatial, and social variables identified during the strategic scope serve as the foundation for this analysis, which maps these variables spatially using GIS, quantifies them through material flow analysis, and contextualizes them socially via stakeholder characterization and network analysis. Together, this multidimensional analysis reveals the interplay between spatial patterns, material fluctuations, and social dynamics, providing comprehensive, context-specific insights into nutrient circularity.

GIS-based analysis visualizes the geographic distribution of activities and associated flows, incorporating land use and administrative boundaries to provide a spatial framework for the analysis. Material flow analysis quantifies nutrient inputs, outputs, and transformations, aligned with the defined material spatial and temporal boundaries established in the strategic scope. Similarly, stakeholder mapping and data collection conducted during the strategic scope establish a baseline for social analysis, enabling the characterization of actors' roles, priorities, and interactions. Visual outputs—such as maps, Sankey diagrams, and social network diagrams—capture localized, sector-specific, and systemic characteristics of nutrient flow management.

SPACE

Basic spatial characteristics, such as administrative boundaries and land use, are initially gathered from local databases and processed using GIS software. Many activity locations, such as wastewater treatment and food processing plants, can be sourced from the PRTR database, which provides detailed geographic information for commercial and industrial organizations. However, individual CP farms are not listed in this database and are often unavailable, so district-level spatial data from agricultural surveys, such as hectares of cropland by crop type per district, and 'agricultural' land use data are utilized. In contrast, AP farms, which commonly generate waste that leaves their premises, are more likely to be registered in the PRTR database. For both CP and AP data, district-level information is typically the most accessible and sufficient for city and regional planning purposes, as strategies primarily focus on land-

based considerations and strategic areas rather than individual farms, particularly smaller ones. For very large farms, more precise location data may be valuable and can be sourced from sectoral association databases if not already included in the PRTR database. CC activities may also require supplementary data sources: green areas can be identified using GIS data from local government archives, while residential populations are typically represented by the 'urban area' classification within land use datasets, often linked to residential density.

The main points of interest in the resulting regional maps are the key activities of each subsystem. This information was integrated with subsequent material flow analysis results to produce basic hotspot or balance maps, illustrating nutrient accumulation or depletion relative to fertilizer demand and nutrient-containing waste flows. While additional spatial and geographic information—such as soil type, topography, and transportation infrastructure—is crucial for designing effective nutrient circularity strategies, these assessments are more appropriate for specific projects and interventions. Therefore, they are reserved for later planning phases beyond this initial regional diagnostic.

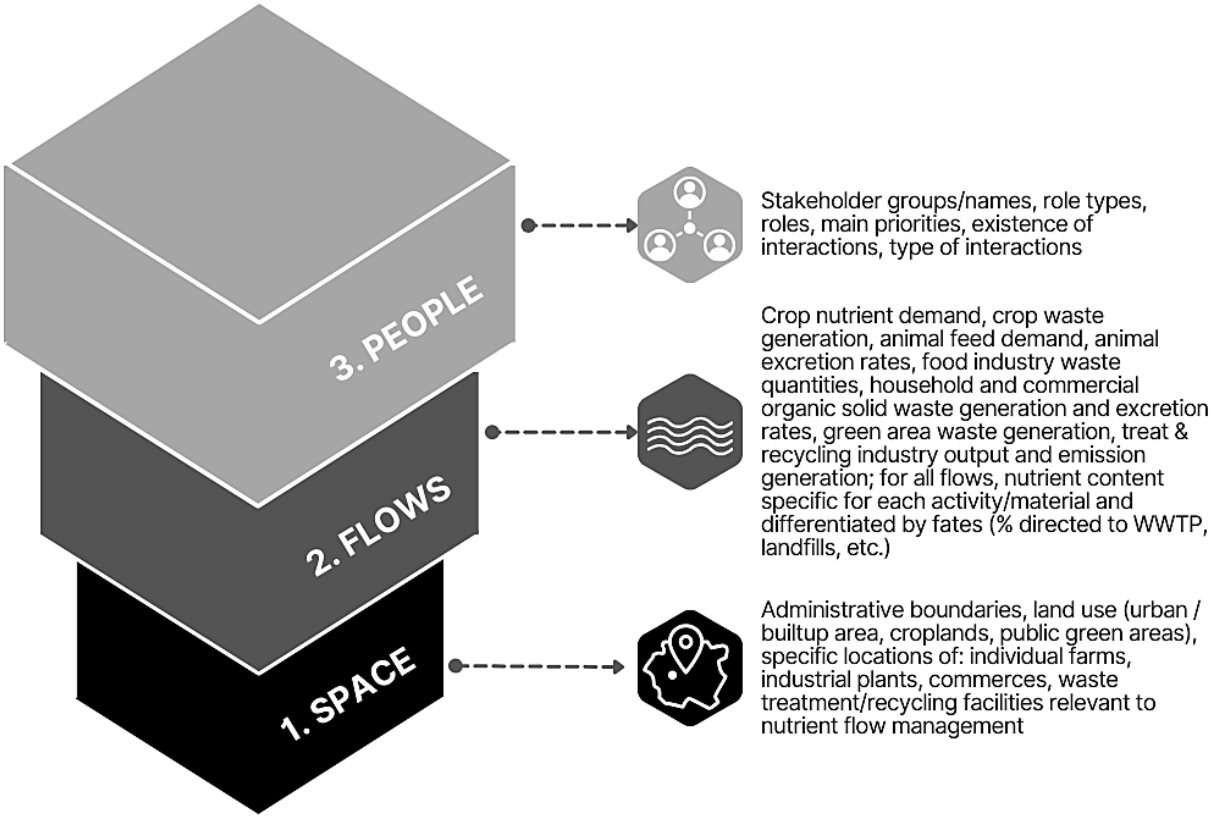

Figure 7. Overview of data inputs for each level in the incremental, multi-dimensional analysis of this diagnostic framework. Detailed descriptions of data inputs are provided in Appendix C.

FLOWS

The scope definition allows for the identification of relevant flow types, which are then assessed in the context of the territory under study. To effectively carry out the material flow analysis, it is

first necessary to: a) select units for measuring and comparing key activities within each subsystem, and b) determine the specific flows of interest between these activities. The choice of units for comparing subsystems is guided by data availability, requiring an initial review to understand the accessible data associated with the identified flow types.

For comparing crop and animal production activities, agricultural surveys—a reliable and widely available data source—can be filtered to the department or district level. Meanwhile, for from food and feed processing industries (FP), commerce and consumption (CC), and waste and recycling treatment facilities (TR), many countries have developed or are in the process of developing a *Pollutant Release and Transfer Register* (PRTR)[1], which provides a detailed data system on local waste generation and management. The units selected for comparing subsystem activities ultimately depend on data availability. In countries where the mentioned data sources are available, the following steps can be applied:

- For CP and AP activities, crop surface area (ha) and livestock units (LSU) are measured using data from local agricultural surveys. Crop surface area is calculated by grouping crops into categories (e.g., 'walnut' under the 'fruit' group) as defined in the surveys and then compared across these groups. This approach accounts for a region's potential diversity of crop types, ensuring their inclusion in future analytical steps.
- The next step involves measuring the amount of nutrient-containing waste (t/y) from FP and TR industries. Data for this analysis can be obtained from the local *Pollutant Release and Transfer Register* (PRTR). This measurement is conducted by filtering data using *European Waste Code* (EWC) classifications and categorizing it based on the source industry type, as defined by the *International Standard Industrial Classification of All Economic Activities* (ISIC). During this process, similar nutrient-containing waste flows from the same activity can be aggregated to determine the total amount for each activity.
- In the CC subsystem, nutrient-containing waste is quantified using both direct and indirect data sources. For commercial activities like restaurants and supermarkets, the PRTR database can be used similarly to FP and TR activities. Meanwhile, domestic and green area waste can be estimated by multiplying population size or surface area by waste generation rates from local technical and scientific publications.

The selection of main activities is done by identifying the activity or activities responsible for at least 50% of the aggregated total for each subsystem (ha, LSU, or t/y), arranged in descending order. Once these key activities are determined, the nutrient-containing input and output flows

[1] The PRTR framework, developed by UNITAR's Chemicals and Waste Management Programme, is being implemented at various stages in countries worldwide. Registries recommend adopting the *International Standard Industrial Classification of All Economic Activities* (ISIC) and international waste classifications, such as the *European Waste Code*, that align with the *Basel Convention*'s efforts to create an international waste management tracking system. More information available at [https://prtr.unitar.org/site/home].

between them are identified using the PRTR database and scientific or technical publications. Finally, the entire system is represented in a systemic diagram, illustrating the region's agri-food-waste subsystems, their primary activities, and the key flows between them.

The analysis then focuses on quantifying flows classified as 'detrimental' and 'opportunity' during the previous definition of the strategic scope. Emphasis is placed on nutrient-containing flows in three primary categories: (a) waste flows from all subsystems that are directed towards TR, final disposal, or lost to the environment; (b) outputs from TR activities or other subsystems that are reused in CP, AP, and/or FP; and (c) input products in CP and AP. Researchers suggests that a more strategic approach to analyzing nutrient circularity may involve considering multiple nutrients, particularly macronutrients (van der Wiel et al. 2019; van Selm et al. 2024). Therefore, nitrogen, phosphorus, and potassium content are calculated for each flow of interest associated with the identified main activities, drawing on literature references, technical reports, and relevant databases. Locally relevant sources, including interviews, should always be prioritized to enhance the accuracy of these calculations, as detailed in Appendix C. To accurately characterize nutrient content across a diverse range of materials, nutrient-containing industrial outputs are categorized as plant tissue, animal tissue, or WWTP sludge, while still preserving the nutrient content specific to each activity or source. Finally, flows are aggregated and visualized through adapted Sankey diagrams for each macronutrient, maintaining a clear distinction among subsystems and their primary activities.

Moreover, hotspot maps were derived from the material flow analysis findings, specifically looking at key sources and demands of nutrient losses and/or demand. These flow quantities and distributions are influenced by factors such as treatment methods for animal waste and existing regulations governing nutrient reuse. These maps can identify areas of nutrient surplus, where outputs exceed local demands, and areas of nutrient deficiency, where nutrient needs surpass what can is or can be supplied by local sources.

PEOPLE

Stakeholder participation was integrated throughout the diagnosis development through semi-structured interviews and meetings with local actors, both for data collection and analyses validation purposes. By reviewing relevant national or regional policy documents or plans, actors from the public, private, and civil sectors involved in their development and validation were identified. From there, actor identification was expanded using the snowball method during interviews. Interviews were carried out in person or virtually through Zoom videocalls, recorded on the same platform, and transcribed using Amberscript software (interview guideline available in Appendix B).

The initial identification of actors is guided by the working groups associated with key regional strategies related to nutrient circularity goals, as outlined in the second paragraph of Section 3. Beyond interview data, official organization websites are also reviewed to gather information on institutional objectives, focus areas, and collaborations with other relevant actors. This information is used to characterize stakeholders based on:

- Their connection to agri-food-waste subsystems
- Their roles as stakeholders, using the classification from Bijon et al. (2023)
- Their main priorities, considering their goals, interests and responsibilities, based on the indicators presented in the next section

In addition to this stakeholder characterization, a social network matrix is also constructed using data from interviews and organizational websites to evaluate actor connections. The matrix is developed within the analytical boundaries set in the initial diagnostic steps and is structured around the question: 'Do these two actors regularly and significantly interact or collaborate on managing key flows?' Responses are categorized into three types of exchanges: organizational (e.g., knowledge sharing or regulatory cooperation), material (exchange of physical products or materials), or both. A lack of response or a '0' is considered a negative answer. The matrix responses are validated by a local expert for enhanced robustness. Finally, the data is processed using Ucinet software to generate social network diagrams. This analysis can identify well-connected actors, isolated individuals or groups, and, by integrating roles and interests, highlights actors with overlapping characteristics (Xu and Zhang 2023; Borgatti et al. 2009; Ghinoi et al. 2020).

3.3.3. UNIFYING INDICATORS

Indicators serve as valuable urban planning tools, synthesizing information to support strategy development and the long-term monitoring of these strategies. In this study, two indicators are proposed, adapted from those outlined in Section 2.3. The final step of the framework involves synthesizing the outputs from the multidimensional analysis into two unifying indicators: Reuse of Nutrients in Agriculture (RNA) and Recovery of Urban Nutrients (RUN). The indicators focus on two critical priorities for cities and regions in the Global South: urban waste management and agricultural resilience.

The Recovery of Urban Nutrients (RUN) indicator addresses this by measuring the proportion of nutrients in raw urban waste (e.g., municipal organic solid waste, domestic wastewater) that are diverted from environmental losses (e.g., discharged to water bodies, landfills) to recovery points where they can be transformed into secondary materials. RUN quantifies nutrient flows originating from the Commerce and Consumption subsystem (the primary source of nutrient losses) that are redirected to Food Processing or Treatment and Recycling Industries. For

example, spoiled supermarket produce can be recovered for secondary food products (CC to FP), while wastewater treatment plants or composting facilities process waste flows into usable materials (CC to TR). This indicator provides a macro-level assessment of a city's recovery efficiency, highlighting deficiencies in waste management systems when RUN values are low. Conversely, high RUN values signal a city's capacity to focus on enhancing reuse efforts, reflected in the complementing indicator: Reuse of Nutrients in Agriculture (RNA) indicator.

The RNA indicator addresses nutrient demand, specifically focusing on agricultural inputs—a critical concern for regions prioritizing food security and local agricultural resilience. The RNA indicator considers only treated waste flows, as raw urban waste carries significant sanitary risks and cannot be directly reused in agriculture. The indicator measures the quantity of nutrients in processed secondary materials—such as sludge and compost—originating from Food & Feed Processing Industries and Treatment & Recycling Industries, which are then reused as inputs for Crop and Animal Production activities. These inputs have the potential to replace or reduce reliance on raw or externally sourced nutrient materials, offering a sustainable alternative for agricultural systems. A low RNA value, which is common in many cities, highlights that even when nutrient recovery (as measured by the RUN indicator) improves, the lack of strategies to reuse these materials in productive activities undermines the benefits of recovery efforts. For instance, while a city might excel in recovering nutrients through wastewater treatment or composting, the absence of mechanisms to reintroduce these materials into local agricultural systems limits their circularity potential. This concern is particularly relevant in regions where food security and agricultural resilience are critical challenges.

Each indicator is linked to specific subsystems, linked to spatial characteristics and trends identified in the spatial analysis. Additionally, the stakeholder analysis connects actors to the priorities associated with these indicators, providing additional social context. Together, the indicators synthesize material, spatial, and social data to reveal critical connections—or disconnects—between urban waste management and agricultural resilience.

$$RUN = \frac{\sum NU_{out\ CC_to_FP\&TR}}{\sum NU_{out\ CC}}$$

(Eq 1)

Where:

$NU_{out\ CC\ to\ FP\&TR}$: total quantity of a specific nutrient (N, P, or K) in t/y from all Commerce & Consumption activities (residual flows) destined to Food & Feed Processing and Waste Treatment & Recovery activities

$NU_{out\ CC}$: total quantity of a specific nutrient (N, P, or K) in t/y from Commerce & Consumption activities

$$RNA_N = \frac{\sum NU_{out\ FP\&TR\ _to_\ CP\&AP}}{\sum NU_{out\ FP\&TR}}$$

(Eq 2)

Where:

$NU_{out\ FP\&TR\ to\ CP\&AP}$: total quantity of a specific nutrient (N, P, or K) in t/y from all Food & Feed Processing and Waste Treatment & Recovery activities (secondary materials) destined to Crop Production and Animal Production activities

$NU_{out\ FP\&TR}$: total quantity of a specific nutrient (N, P, or K) in t/y from Food & Feed Processing + Waste Treatment & Recovery activities

Although these indicators are grounded in the quantification of nutrient recovery and reuse inputs and outputs, they also integrate spatial and socioeconomic information to assess circularity performance across activities and actors within the study area. The spatial analysis highlights trends in the distribution of subsystem activities, and because each indicator is associated with specific subsystems, it can reflect spatial characteristics, such as urban, rural, or peripheral contexts. Furthermore, since stakeholder characterization incorporates nutrient circularity principles linked to each indicator, these indicators can also be aligned with the priorities of specific actors.

3.4. CASE STUDY RESULTS: THE METROPOLITAN REGION OF SANTIAGO

3.4.1. Main activities and flows

The diagnostic framework was applied to the Metropolitan Region of Santiago de Chile (MRSC), which was identified as having the second highest Nutrient Circularity Capacity in the region (Fleitas Girett et al., 2023). Centrally located within Chile, the MRSC hosts approximately 40% of the nation's population and contributes 48% to the national GDP (CEPAL 2022). Historically, the region has benefited from fertile soils, enabling substantial agricultural output, particularly in vegetables and fruits (Yánez Barrios 2021). However, like many South American urban centers, the MRSC has experienced rapid urbanization, especially in its peripheral rural areas (Gottshalk et al. 2022; Silva 2020). In response to these sustainability challenges, national institutions such as the 'Circular Economy Office' and the 'Sustainability and Climate Change Agency' (ASCC) have been established to improve waste management, implement Extended Producer Responsibility (EPR) legislation, and promote recycling and circular economy initiatives. Moreover, the National Organic Waste Strategy aims to increase organic waste recovery from municipal sources from 1% to 66% by 2040, involving key institutional stakeholders.

Data collection for this diagnostic framework focused on activities and flows within the MRSC's administrative boundaries, encompassing six provinces and 52 communes. The year 2021 was chosen for data collection, as it provided the most up-to-date information from the recent agricultural survey, which was crucial for this research. In addition to a comprehensive literature review, 34 semi-structured interviews were conducted with representatives from government institutions, private companies, and civil and academic organizations.

Following the procedures outlined in Section 3.1 and Appendix C, the main activities within each subsystem were identified and represented in a regional system diagram (Figure 8). This diagram illustrates the primary agri-food-waste system activities in the MRSC and the main nutrient-containing flows exchanged both within the region and with external subsystems. This served as the foundation for the multidimensional analysis, which concentrated on flows categorized as 'detrimental' or 'opportunity' materials."

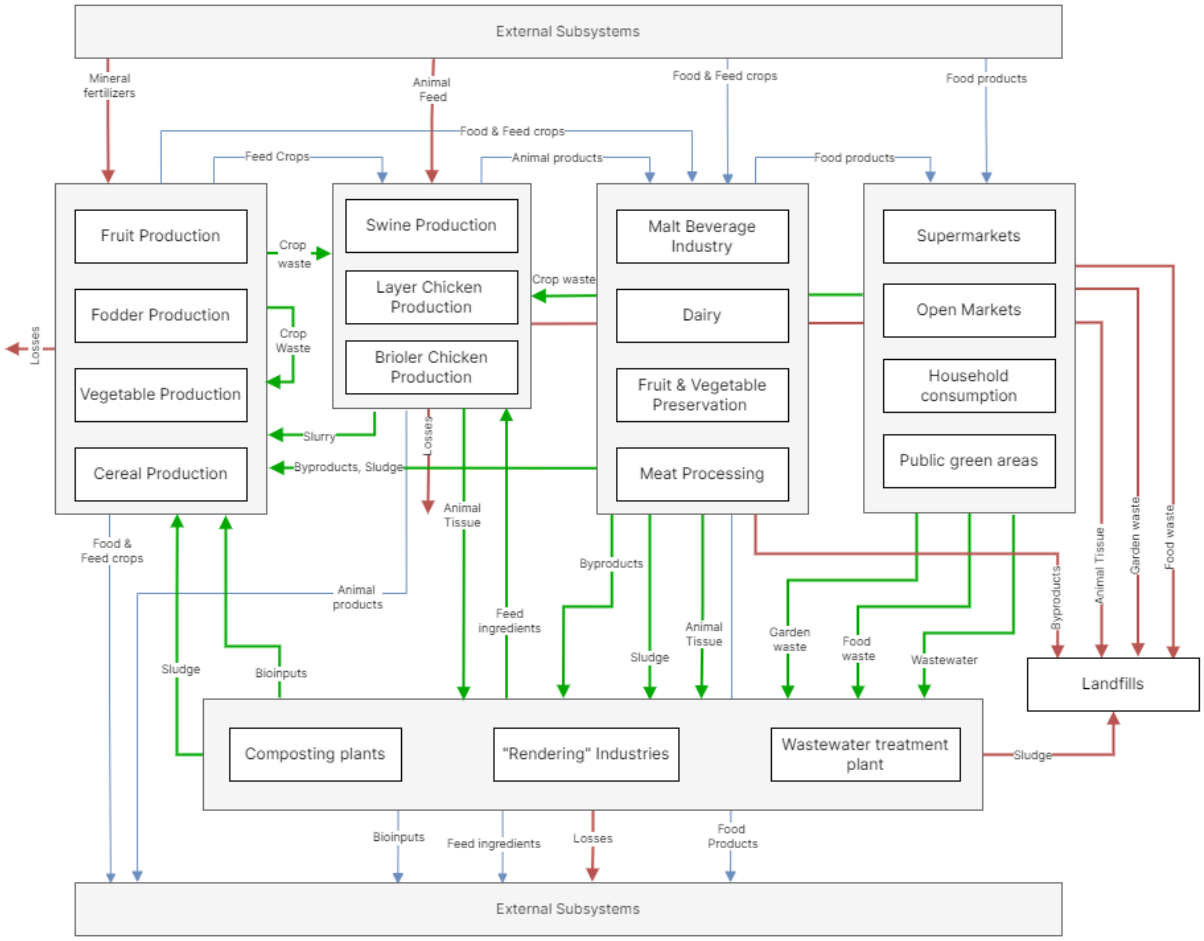

***Figure 8**. System diagram of main activities and flows in the MRSC. Following the same coloring code as Figure 6, the arrows represent the main nutrient-containing materials exchanged to and from the main subsystems and their activities, as well as those external to the MRSC.*

3.4.2. Space

The districts of the Metropolitan Region of Santiago were mapped based on the findings of (Rodríguez Vignoli 2017), who grouped the districts into 12 “large zones” considering local urbanization trends. Geospatial data was collected from various sources, including:

- Mapoteca of the Library of the National Congress of Chile: https://www.bcn.cl/siit/mapoteca
- Natural Resource Information Center database: https://bibliotecadigital.ciren.cl
- IDE Chile database: https://www.ide.cl
- Territorial Statistical Consultation System of the National Office of Agrarian Policy & Studies (ODEPA): https://icet.odepa.gob.cl
- Territorial Information System of the National Forest Corporation (CONAF): http://sit.conaf.cl

Locations of AP, FP, CC, and TR activities were identified using the local PRTR database, though this resource only included large industrial plants, excluding smaller AP farms. Due to

data limitations, the distribution of CP farms and CC households was represented using agricultural and urban land-use data.

The spatial analysis of subsystems revealed patterns consistent with expected urban-rural distinctions (Figure 9). CC activities are heavily concentrated in urban areas (depicted as dark grey on the map), reflecting their urban-centric economic nature. FP industries (marked as double circles) and TR facilities (encircled triangles) are predominantly situated in the peripheral areas surrounding urban centers, indicating functional interconnections and strategic positioning. FP activities display a spatial distribution based on their raw material sources: industries relying on imported inputs, such as malt beverage and dairy processing, are located close to the urban market, while those utilizing MRSC agricultural produce, like slaughterhouses and fruit processors, are positioned in peripheral, agriculturally active areas along major logistical routes. TR facilities, including composting plants, major landfills, and wastewater treatment plants, are clustered in the western peri-urban region, with some extending further from Santiago's center into built-up areas significant for crop production, all located near the main waterways of the Maipo River basin. Rendering plants are concentrated in southern rural areas, close to both animal and crop production zones.

Analysis of CP activities (Appendix D) shows a predominant focus on fruit production, including wine grapes, which collectively cover around 59% of cropland. Cereal production, primarily maize, is concentrated in the Melipilla province, located in the southwest of the region. Market gardening occurs on cropland near the urban center, though census data indicate a decline in market gardening land. The AP subsystem also displays distinct spatial trends: large pig and broiler farms (red lined and filled-in circles) are highly concentrated in Melipilla province, especially in San Pedro, with interviews revealing a movement of these farms toward the neighboring southern region of O'Higgins. In contrast, layer farms are smaller and more dispersed throughout the region.

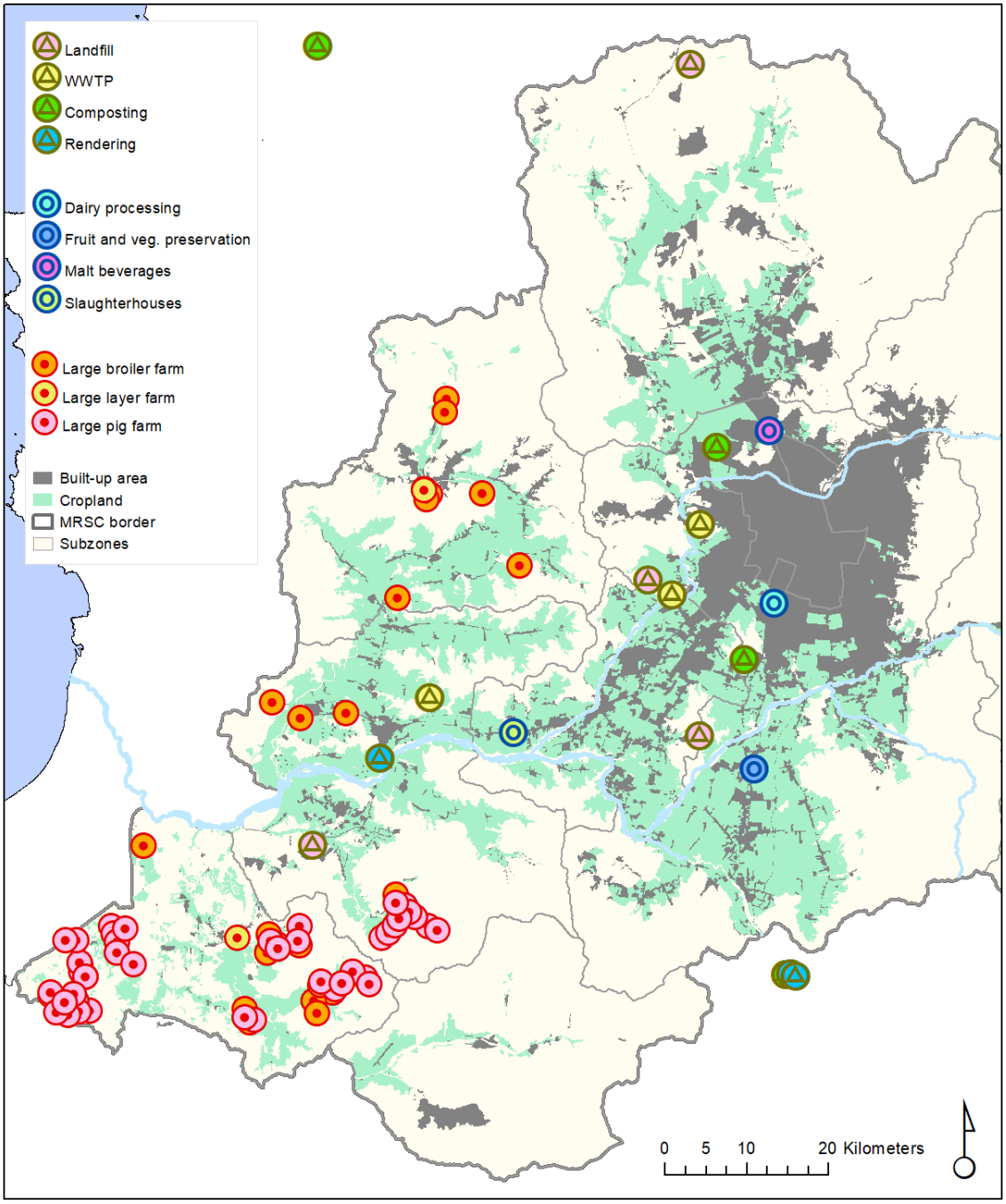

Figure 9. Map of key agri-food-waste system activities in the MRSC. Different icons represent different subsystems, while the variation of colors represents different activities within each subsystem. As described in Section 3.1, CP and CC are represented through land use (cropland, built-up area), and only large farms of AP are identified.

3.4.3. Space + Flows

Analysis of the flow dimension enabled the quantification of nitrogen (N), phosphorus (P), and potassium (K) flowing between the main activities in the region, as well as losses to the environment. Quantifications were conducted for each primary activity, and **Error! Reference source not found.** summarizes the aggregated N, P, and K flow values between subsystems.

These quantified flows were visualized using strategic, hybrid Sankey diagrams, developed based on the system design (**Error! Reference source not found.** & Appendix E).

Table 1. Summary of nitrogen (N), phosphorus (P), and potassium (K) flow amounts (t/y) to, from, and between subsystems, including inputs from mineral fertilizers and flows directed to the environment (considered as losses) or unknown destinations.

From	To	N	P	K
Mineral Fertilizers	Crop Production	10,795	1,427	7,600
Crop Production	Animal Production	48	9	42
Crop Production	Soil	977	93	737
Crop Production	Environment / Loss / Unknown	324	4	73
Animal Production	Crop Production	8,084	2,926	7,736
Animal Production	Treatment & Recycling	1,365	347	1,128
Animal Production	Environment / Loss / Unknown	11,283	77	187
Animal Production	Landfill	66	4	54
Food & Feed Processing	Animal Production	1,177	160	77
Food & Feed Processing	Treatment & Recycling	2,592	487	1,529
Food & Feed Processing	Landfill	650	154	105
Commerce & Consumption	Treatment & Recycling	42,649	6,810	10,732
Commerce & Consumption	Landfill	11,552	1,105	9,948
Commerce & Consumption	Environment / Loss / Unknown	471	75	118
Non-Agrifood Sources	Treatment & Recycling	300	88	41
Non-Agrifood Sources	Landfill	233	10	57
Treatment & Recycling	Crop Production	3,254	1,490	265
Treatment & Recycling	Environment / Loss / Unknown	39,384	4,816	10,979
Treatment & Recycling	Landfill	1,331	623	108
Treatment & Recycling	Compost	791	657	312
Food & Feed Processing (external)	Animal Production	28,075	5,143	7,475

Key findings from the analysis of nutrient flows among sectors of activity are summarized below, with a more detailed discussion of MRSC results provided in Appendix F.

Nutrient Demand:

- All CP activities meet crop nutrient requirements using commercial fertilizers, primarily applying urea, often supplemented with phosphorus, potassium, or NPK-mix fertilizers.
- Fruit trees generally receive higher potassium inputs, while phosphorus applications are comparatively lower.
- Data on the use of commercial bio-inputs, such as compost and organic fertilizers, for CP activities and urban green spaces remains limited.
- Animal feed production heavily relies on imported soy, maize, and wheat products, though some feed additives are sourced from local rendering and FP outputs.

Nutrient Supply:

- CP and AP activities primarily generate unprocessed waste materials, such as crop residue, manure, and animal tissue, while FP activities produce both raw byproducts (plant and animal tissue) and processed outputs, such as WWTP sludge.
- Households in CC activities contribute significantly to nitrogen, phosphorus, and potassium within the system, mostly as unprocessed output materials, and lead to substantial nutrient losses through organic solid waste in landfills.
- TR activities release processed materials, including treated water, sludge, and compost, but limited information is available regarding their quantities and final destinations.
- Interviews reveal that farmers often overlook the nutrient contribution of AP manure application, leading to nutrient overaccumulation and environmental losses in CP.
- Concerns about nutrient excess and associated losses are heightened by reports that pig slurry, layer manure, and sewage sludge are mainly spread on cereal and industrial cropland. Notably, the fruit sector, which has the highest nutrient demand, appears to receive minimal or no recycled nutrient inputs.

The Sankey diagrams from the material analysis illustrate nutrient losses to the environment. Nitrogen (N) is predominantly released into the atmosphere, thereby avoiding significant local impacts, while phosphorus (P) and potassium (K) are discharged into soil or surface water. When combined with spatial analysis, this reveals additional insights.

- Sludge nutrients from Santiago's two main WWTPs are primarily applied to cereal cropland and travel 20-30 kilometers west, discharging effluent into a major Maipo River branch that flows to the Pacific Ocean. By combining observed phosphorus content near the MRSC outlet (0.5 mg/L) with the average annual river discharge (123 m^3/s), it is estimated that one-third of the phosphorus in the basin discharge originates from WWTPs, identified as the dominant source. River water quality data show minimal upstream phosphorus (P) concentrations, indicating that the phosphorus primarily comes from local,

anthropogenic sources. This supports the finding that phosphorus from waste applied to soil tends to remain stored in the soil. Furthermore, the analysis suggests that phosphorus from WWTP discharge may be unintentionally used for crop irrigation, as low discharge rates have been documented due to excessive water extraction for irrigation (Lagos del Río, F. A. 2023).

- As shown in **Error! Reference source not found.**, subregional AP nutrient emissions range from comparable to CP demand to being significantly lower or higher. Where emissions and demand are similar, phosphorus emissions primarily originate from layer farms, suggesting an opportunity for planners to consider converting layer-to-land flows into local recycling schemes that could substitute commercial fertilizers. In contrast, the situation in the southwestern zones is markedly different, with AP nutrient emissions far exceeding CP demand. This discrepancy is particularly pronounced in San Pedro, where excess nutrients cannot be feasibly used to fertilize crops in neighboring MRSC zones, even if commercial fertilizers were substituted. It is likely that these surplus nutrient flows are currently directed to land outside the MRSC boundary, a factor that could influence planners' approach to addressing nutrient management and recycling strategies.

Overall, the MRSC functions as a significant nutrient sink. Annually, about 70,000 tons of nitrogen contained in waste are lost within the MRSC. Phosphorus losses amount to roughly 11,000 tons per year, and potassium losses total around 33,000 tons per year. This information is visualized in Sankey diagrams of regional level material flows between all subsystems.

In the MRSC, heatmaps indicated that AP nutrient surpluses far exceeded CP needs in southwestern zones, particularly in San Pedro, highlighting the need for redistribution or nutrient export strategies. This spatially explicit information can help planners and policymakers develop targeted interventions to address nutrient accumulation hotspots that may cause contamination and to connect nutrient-deficient agricultural areas with nearby nutrient-surplus zones. Additionally, the proximity of nutrient-deficient areas to treatment and recycling facilities can inform infrastructure planning to optimize the flow of secondary nutrients, reducing reliance on imported inputs and supporting regional food security.

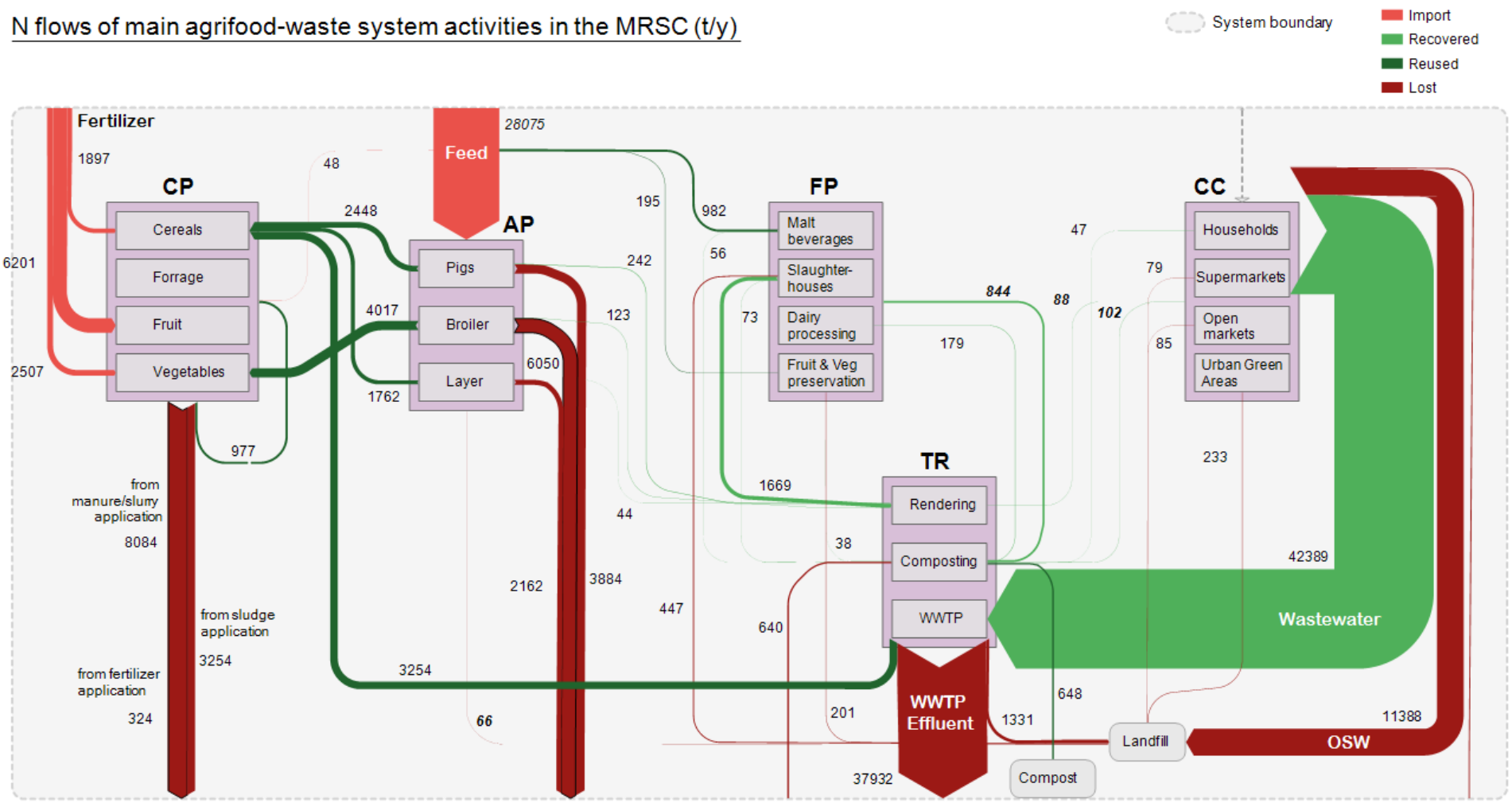

Figure 10. Adapted Sankey diagram of nitrogen (N) flows (t/y) to, from, and between main activities across the agri-food-waste subsystems of the MRSC in 2021. Dark red flows indicate nutrient losses to the environment, landfills, or unknown destinations; light green flows represent nutrient recovery (to TR); dark green flows show reused nutrients (to CP and AP); and light red flows depict nutrient imports (to CP and AP). Corresponding Sankey diagrams for phosphorus (P) and potassium (K) can be found in Appendix E

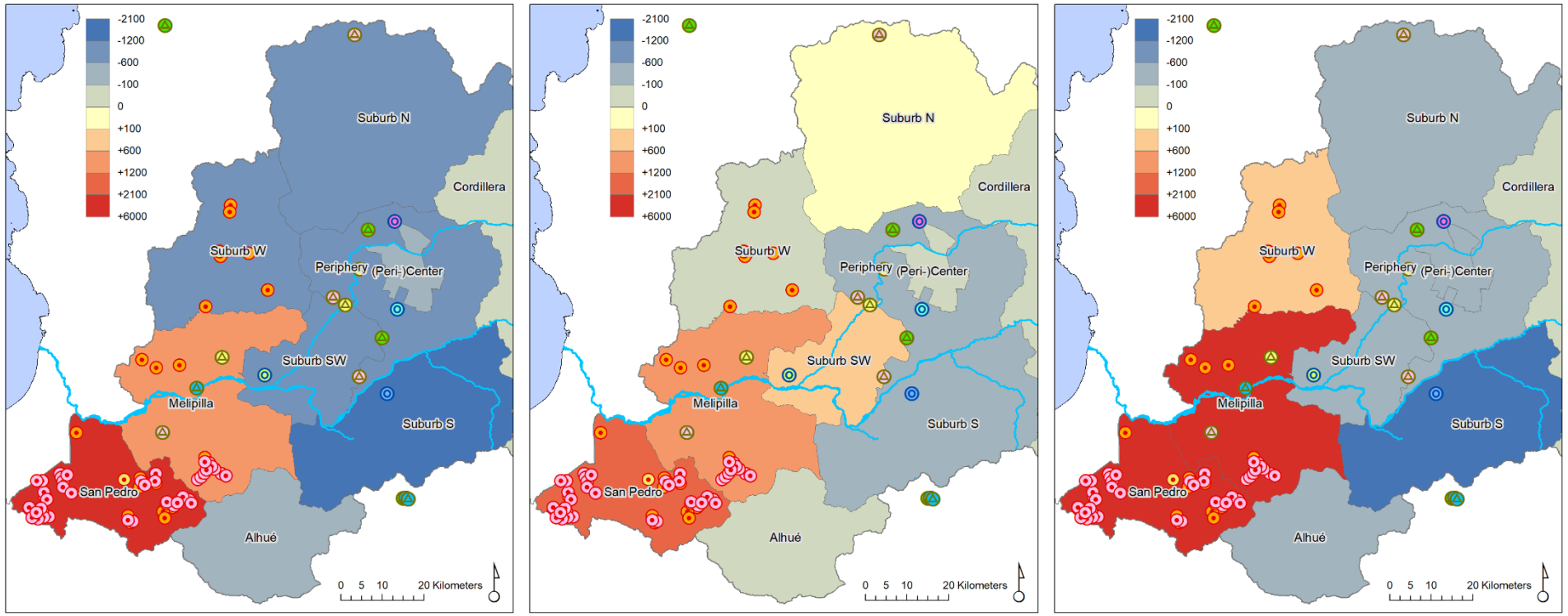

Figure 11. Heatmaps illustrating N (a), P (b), and K (c) surpluses or deficiencies between agricultural subsystems by geographic zone (based on Rodríguez Vignoli, 2017). The maps are based on the nutrient demands of CP activities and the nutrient supply from AP activities in 2021. Blue tones represent nutrient deficiencies, while red tones indicate nutrient surpluses.

3.4.4. Space + Flows + People

The “people” dimension produced a comprehensive list of key actors directly or indirectly involved in local nutrient circularity. A total of 45 actors were identified and classified based on (a) their role types, using Bijon et al.’s framework of material and influential roles, and (b) the indicator reflecting their primary interest or concern, as summarized in **Error! Reference source not found.**. The analysis identified 12 material actors, 28 influential actors, and 5 actors who fulfill both roles. When evaluating their priorities—specifically, the recovery of urban output materials (RUN) versus the reuse of secondary materials in agricultural activities (RNA)— 21 actors prioritized RNA, 16 focused on RUN, and 8 addressed both aspects. This highlights the collaborative nature of nutrient circularity efforts, involving a diverse set of stakeholders with distinct roles and responsibilities.

Key insights from this characterization include:

- Material Actors focused on RNA: Collaboration between farms and processing facilities could enable the implementation of on-site nutrient recycling systems and integrated nutrient recovery efforts, which may contribute to soil health and reduce dependency on synthetic fertilizers.
- Material Actors focused on RUN: Urban waste generators and handlers can enhance nutrient recovery through improved waste segregation, better recycling infrastructure, and community-driven composting initiatives. Collaboration with waste processing facilities and local authorities could help optimize nutrient capture from urban waste.
- Influential Actors focused on RNA: Actors such as research institutions and agricultural associations have the potential to influence nutrient reuse practices through advocacy, educational programs, and policy development. Coordinated efforts may facilitate the promotion of sustainable agricultural practices, including the use of bio-fertilizers and organic waste recycling, by providing farmers with relevant resources and knowledge.
- Influential Actors focused on RUN: Urban regulatory bodies and community associations play a role in shaping nutrient recovery practices through policy formation and public engagement. Coordinated actions, such as regulatory enforcement, awareness initiatives, and incentives for sustainable practices, may support the advancement of urban nutrient recovery.

The stakeholder interaction data, captured as binary responses (yes = 1, no = 0), was compiled into a stakeholder matrix spreadsheet. This matrix was uploaded to Ucinet, an open-source software designed for social network analysis, to generate social network diagrams. Within these diagrams, actors are represented as “nodes,” while their interactions are represented as

“edges.” The node size in the diagrams reflects the number of connections each actor has with other nodes, providing a visual representation of their centrality within the network. By visualizing these relationships, the social network diagrams advance understanding of the nutrient management system’s social dimension.

The semi-structured interviews played a critical role in generating the diagram by exploring how organizations engage with nutrient-containing flows, their collaboration with other sectors or actors, their interaction with government or academic institutions, and their recommendations for additional stakeholders to include in the analysis. These responses were cross-referenced with existing records and expert feedback to ensure accuracy and comprehensiveness.

According to the Social Network Analysis (Appendix G), key actors involved in Reuse of Nutrients in Agriculture (RNA) include rural municipalities, the Agricultural and Livestock Service (SAG), the Ministry of Agriculture (SEREMI Agricultura), the National Agricultural Research Institute (INIA), universities, and farmers, all of whom demonstrate high levels of interaction. In contrast, actors with lower levels of interaction include the Regional Government, bio-fertilizer associations, the Agricultural and Livestock Information Office (ODEPA), the Chilean Association of Agro-Industrialists (ACHIPIA), extensionists, FP industries and their associations, and rendering industries.

For the Recovery of Urban Nutrients (RUN) priority, the most interactive actors include rural and urban municipalities, the Ministry of Health (SEREMI Salud), the Ministry of Environment (SEREMI Ambiente), and local residents. In contrast, actors with lower levels of interaction are the Ministry of Housing and Urban Development (MinVu), regional government bodies, vendor associations, community groups, environmental consultants, the Environmental Assessment Service (SMA), the Production Development Corporation (CORFO), INIA, open markets, and

restaurants.

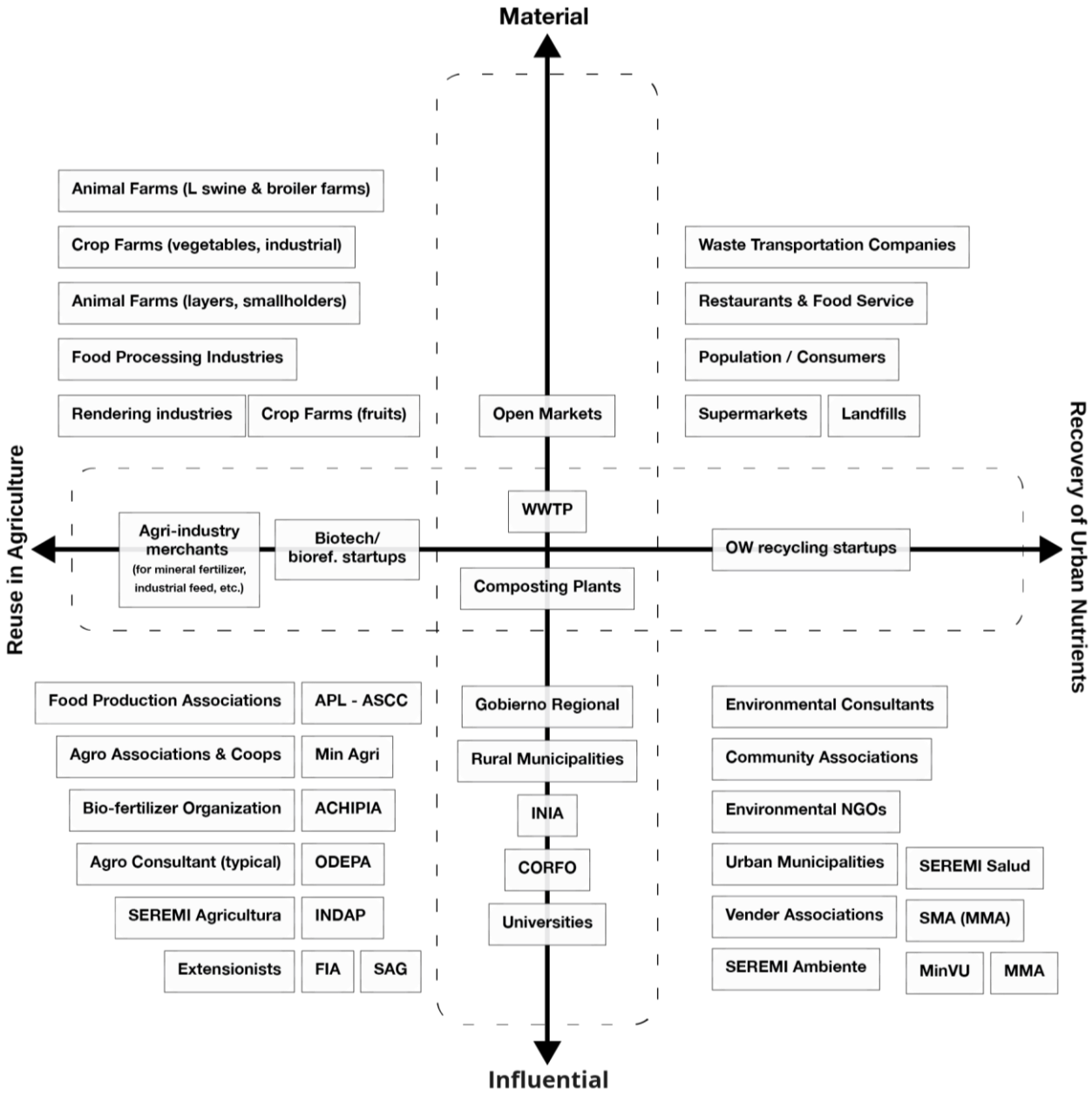

Figure 12. Characterization of the agrifood-waste system actors in the MRSC, considering priority indicator (Recovery of Urban Nutrients or Nutrient Reuse in Agriculture) and role type (Material or Influential).

3.4.5. INDICATORS

Nutrient circularity indicators provided an integrated and comparable metric for measuring urban nutrient recovery and agricultural nutrient reuse across urban and rural areas of the region, effectively combining material and spatial dimensions. The RUN indicator scores (Table 2) were calculated and converted into percentages, showing recovery rates of 78% for nitrogen (N), 85% for phosphorus (P), and 52% for potassium (K). Collectively, the recovery indicator for N+P+K stands at 72%, indicating that nearly three-quarters of urban nutrient outputs are directed to facilities capable of partially transforming them into secondary materials or products.

This high score is largely due to the processing of urban wastewater at wastewater treatment plants (WWTP), but it is negatively impacted by the loss of organic solid waste that is still being sent to landfills.

Table 2. RUN indicator values for different nutrient types, showing the percentage of total nutrient flows recovered from commerce and consumption (CC) outputs to treatment/recycling and food processing (TR + FP) inputs.

Type of Nutrient	Total Nutrients from CC (t/y)	Total Nutrients from CC to TR + FP (t/y)	Recovered urban nutrients
N	54,672	42,649	78%
P	7,990	6,810	85%
K	20,799	10,732	52%
N+P+K	83,461	60,191	72%

Meanwhile, nutrient reuse indicator scores (Table 3) are 11% for nitrogen (N), 27% for phosphorus (P), and 5% for potassium (K). When combined, the overall reuse rate for the three macronutrients is just 12%, indicating a very low proportion of recovered nutrients being applied as secondary materials in productive activities. These low values are likely attributed to (a) regulatory restrictions on the use of animal excreta and wastewater treatment plant (WWTP) sludge, (b) technological limitations in retaining nutrients for reuse in secondary materials, and (c) the limited adoption of organic fertilizers by farmers.

Table 3. RNA indicator for different nutrient types, showing the percentage of total nutrient flows reused from treatment and recycling (TR + FP) outputs to agricultural crop or animal production (CP + AP) inputs.

Type of Nutrient	Total Nutrients from FP + TR (t/y)	Total Nutrients from FP + TR to CP + AP (t/y)	Reuse of NUTRIENTS in Agriculture
N	49,180	5,222	11%
P	8,386	2,306	27%
K	13,376	654	5%
N+P+K	70,942	8,182	12%

When these indicators were integrated with the social dimension, findings regarding urban nutrient recovery reveal the central role of municipal governments and health and environmental ministries, underscoring their significance in managing nutrient flows. Given the material flow analysis, wastewater treatment plants (WWTPs) also emerge as critical actors for planning interventions and should be considered central in this context. However, the absence of an influential actor on the receiving end of secondary material flows suggests that establishing an organizational link with SEREMI Ambiente could strengthen planning efforts. Additionally, the limited engagement of entities like MinVu, regional government bodies, and community associations highlights missed opportunities to integrate urban nutrient management more comprehensively with housing and urban development policies.

Regarding nutrient reuse in agriculture, findings suggest that rural municipalities, agricultural institutions (such as SAG, SEREMI Agricultura, and INIA), and universities are well-positioned to lead nutrient reuse initiatives, owing to their strong interaction networks. This is particularly significant given that spatial and material analyses show that some AP nutrient-emitting activities span diverse communities, necessitating engagement with numerous medium- to small-scale holdings. Conversely, analyses also highlight the significance of large pig and broiler farms in the southwestern region, which are centrally managed by one or two major holdings. In this distinctly different context, urban planners and public officials on the 'influential' side would likely prioritize establishing common ground with these central actors to drive change effectively. Additionally, stakeholder analyses reveal lower interaction levels among bio-fertilizer associations, FP industries, and rendering industries, indicating potential gaps in engagement and capacity among actors who could be critical but are currently disconnected or insufficiently integrated.

3.5. Discussion

Effective and sustainable nutrient circularity strategies require comprehensive and strategic information on nutrient-flow management. This research addresses this need by integrating methodologies from urban metabolism and urban planning, combining spatial, material flow, and stakeholder analyses into a strategic territorial diagnosis. This approach enables the identification of key areas, activities, and actors critical to nutrient circularity, particularly in relation to nutrient losses, contamination risks, and recovery potential.

The study underscores the relevance of a systemic and circular approach to urban nutrient management, advocating for evidence-based, context-specific insights rather than reliance on assumptions and estimations. By aligning nutrient flow assessments with urban planning processes, the framework enhances decision-making by providing a structured, adaptable model tailored to diverse urban systems, with particular applicability to the Global South. Using the Metropolitan Region of Santiago—a leader in nutrient circularity capacity—as a case study, the research highlights transferable insights that can inform planning initiatives in other urban contexts facing similar challenges. Additionally, the diagnostic approach developed here is designed to be flexible and scalable, supporting broader efforts in circular resource management across varying urban environments.

3.5.1. Diagnosis Results for MRSC

Main Challenges:

The MRSC faces significant challenges in nutrient management, primarily due to reliance on imported nutrients and insufficient soil nutrient control, which hinder nutrient circularity. These

findings align with Salazar et al. (2015) and Corradini et al. (2015), who highlighted nutrient imbalances in soils and water bodies of the region. Despite high nutrient recovery potential in urban areas, substantial organic waste losses persist. The AP sector and urban sanitation systems tend to minimize nitrogen management to reduce operational demands, leading to inefficiencies. Limited municipal budgets, shaped by socioeconomic and political factors, constrain logistics and technology investments, hampering effective waste management (Javiera & Acuña, 2021; Sepúlveda & Sánchez, 2021).

Regulatory limitations, lack of awareness, and distrust in recycled products further weaken nutrient recovery (ODEPA et al., 2019). Additionally, circular agriculture and organic fertilizer engineering are absent from university curricula, creating a shortage of qualified professionals to advance nutrient recovery and reuse. Urbanization pressures reduce agricultural land availability, limiting treatment and recycling capacities. The disconnect between rural and urban areas and across sectors hinders region-wide resource management. Moreover, research and development concentration in the private sector restricts knowledge dissemination and innovation (van der Wiel et al., 2019).

Existing strategies primarily focus on urban nutrient recovery while neglecting nutrient reuse, leading to nutrient accumulation in urban sinks. Key policy documents fail to address nutrient efficiency, recovery, and agricultural partnerships. For instance:

- The Ministry of Agriculture's agrifood strategy omits nutrient use efficiency, losses, and recovery (Qualitas Agroconsultores Ltda., 2021).
- The National Food Security Strategy lacks references to recovered nutrient use (Javiera & Acuña, 2021).
- The "Agenda for Municipalities Facing Climate Change" does not recognize agricultural institutions as relevant actors in municipal organic waste management (Adapt Chile, 2017).

Without addressing these policy gaps, nutrient circularity in MRSC remains constrained, limiting its potential for sustainable nutrient management.

Opportunities:

Despite these challenges, rising fertilizer costs, increasing water scarcity, and supportive policies are promoting interest in organic bio-inputs, promoting sustainable agricultural practices (Javiera & Acuña, 2021). Policies such as crop residue burning bans indirectly enhance nutrient recovery by reducing soil depletion (Sepúlveda & Sánchez, 2021). The proximity of TR facilities to agricultural areas presents a unique opportunity to develop circular agricultural practices that efficiently cycle nutrients back into the soil. The diverse agri-food-waste subsystems in MRSC offer potential synergies to optimize nutrient flows.

Establishing integrated resource management strategies can enhance sectoral collaboration and efficiency. Technological innovations, such as alternative water treatment methods (e.g., struvite precipitation, source separation systems), pre-diversion of nutrient-rich flows before wastewater collection, and utilization of recovered nutrients for urban green spaces, can significantly enhance nutrient recovery and support sustainable nutrient demand. By advancing these opportunities, the MRSC can move towards a more resilient and efficient nutrient circularity model, addressing key challenges while unlocking regional sustainability potential.

3.5.2. Methodological Contributions and Implications

The importance of interdisciplinary approaches in nutrient circularity research has been consistently highlighted (McGreevy et al., 2022; Poponi et al., 2022; Stamm et al., 2022). This study integrates urban metabolism and urban planning frameworks to develop a regional diagnostic model that informs local planning processes in the Metropolitan Region of Santiago (MRSC). Through a structured series of steps (Figure 13), this study develops a strategic, multidimensional framework for regional nutrient flow management. This framework consolidates spatial, material flow, and stakeholder analyses, ensuring a holistic understanding of urban nutrient dynamics. By systematically identifying key challenges and opportunities, this approach strengthens the strategic alignment of nutrient circularity goals within urban and regional governance structures. The final methodological step, which will expand on policy integration and implementation pathways, will be further explored in a forthcoming paper.

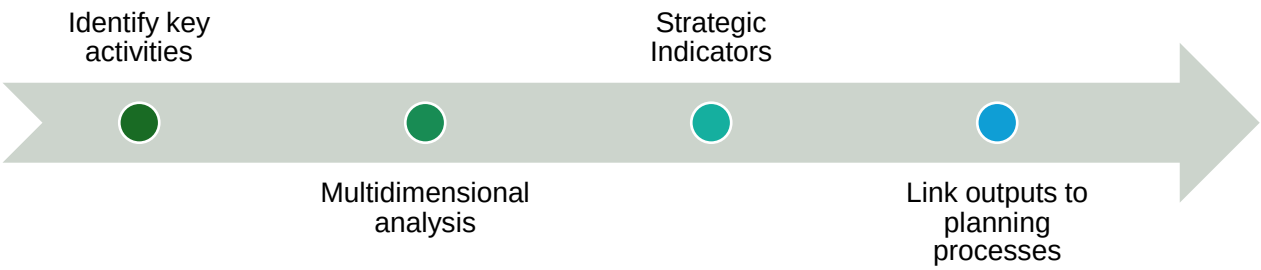

Figure 13. The key methodological steps included in this regional nutrient-flow management diagnosis, intended for actors involved in the assessment phase of strategic urban planning.

3.5.3. Strategic Scope

Defining a preliminary strategic scope is critical to ensuring that the diagnostic framework remains both comprehensive and actionable. The selection of key agri-food-waste activities was based on their quantifiable contribution to nutrient-containing flow inputs and outputs (T/y) and their environmental and social impact within the local context. By balancing macro- and micro-scale perspectives, the framework collects data at the metropolitan scale while structuring processing and output flows at the subsystem level. This approach ensures that the framework captures both localized concerns and system-wide interconnections, facilitating its application in urban planning and nutrient management strategies. This enables precise linkages between nutrient circularity strategies, specific actors, and policy mechanisms, bridging the gap between high-level planning goals and localized implementation needs. Given the diverse range of agri-food-waste system activities in the MRSC, careful selection of key activities and flows was essential to minimizing assumptions and enhancing interpretability.

The PTCR database was chosen as the primary data source due to its broad availability and adaptability in many countries worldwide, as well as its capacity to provide a transparent, real, and reproducible foundation tailored for nutrient flow management. Despite the presence of high-quality datasets in the region, data fragmentation and variability in quality pose challenges to effective utilization. By prioritizing key activities and nutrient flows, this diagnostic provides a context-specific yet adaptable framework for urban nutrient circularity planning. Moreover, the preliminary classification of flows developed here is potentially transferable to other urban contexts, particularly in the Global South (Coq-Huelva & Asián-Chaves, 2019; Da Gama Torres, 2011).

3.5.4. Multidimensional Analysis

A multidimensional approach is essential for understanding nutrient flow dynamics and designing effective circularity strategies. By integrating spatial, material, and social analyses, this study provides a comprehensive diagnostic that identifies inefficiencies, intervention points, and opportunities for systemic improvements in nutrient management. Urban studies have highlighted two major trends affecting nutrient circularity: the decline in agricultural land and the uncoordinated expansion of urban areas. By linking these land-use trends to nutrient flow dynamics, this framework provides a systemic perspective on how urbanization pressures influence resource management. Understanding these interconnections allows for a more targeted and strategic response to nutrient circularity challenges, ensuring that planning efforts align with sustainability objectives (Wielemaker et al., 2019; Metson et al., 2022).

The material flow analysis quantifies nutrient accumulation, losses, and recovery using localized data and Sankey diagrams to present a sector-wide overview. Unlike prior studies that isolate

subsystems or rely on broad assumptions, this analysis uses granular, location-specific data to highlight nutrient inefficiencies and potential recovery pathways. When integrated with spatial insights, this allows for precise identification of infrastructure gaps and policy-relevant recovery strategies. For example, the proximity of urban Commerce and Consumption (CC) activities to Food Processing (FP) and Treatment and Recycling (TR) facilities suggests opportunities for circular hubs that optimize nutrient recovery and redistribution. Heatmaps of nutrient surpluses and deficiencies support targeted resource redistribution, such as relocating manure from surplus areas to nutrient-deficient zones, reducing dependence on synthetic fertilizers (Metson et al., 2018). By integrating spatial and material insights, planners can design targeted interventions that enhance self-sufficiency, food security, and resource efficiency (Annevelink et al., 2017).

Understanding the roles and relationships of key actors is fundamental to advancing nutrient circularity (Macintosh et al., 2019). For this, the semi-structured interviews conducted in this study further validated stakeholder roles and identified missing actors within the nutrient management system. Responses were cross-referenced with existing records and expert feedback to ensure accuracy and comprehensiveness. This resulted in stakeholder mapping, characterization and social network analysis.

Stakeholder mapping and characterization help determine who directly manages nutrient flows, who influences policy and practices, and who holds dual roles and can serve as strategic mediators. This differentiation allows for targeted interventions and the inclusion of often-overlooked stakeholders who play critical roles in nutrient circularity strategies (Bijon et al., 2023). In addition, the resulting social network diagram visualizes relationships, weak connections, and gaps, providing actionable insights for improving coordination and encouraging stronger partnerships. Social network analysis findings reveal coordination gaps between urban and rural actors, institutional silos that hinder cross-sector collaboration, and potential partnerships that align with circular economy objectives. Highly connected actors, such as rural municipalities and agricultural institutions, are well-positioned to lead nutrient recovery initiatives, while underconnected stakeholders may require targeted engagement strategies to enhance system-wide coordination.

By synthesizing spatial, material, and social analyses, this framework translates complex system interactions into actionable insights. This ensures that findings are not only theoretically robust but also strategically relevant, supporting policymakers in prioritizing infrastructure investments, enhancing cross-sector coordination, and integrating nutrient circularity into broader sustainability frameworks. By providing a shared language and metrics, this framework encourages cross-sector collaboration, breaking institutional silos and promoting synergistic solutions for sustainable nutrient circularity.

3.5.5. Indications

Building on the multidimensional analysis, RUN (Recovered Urban Nutrients) and RNA (Reused Nutrients in Agriculture) indicators serve as concise, high-impact metrics that support decision-making in nutrient circularity. These indicators explicitly link nutrient recovery and reuse patterns to spatial distribution and stakeholder roles, addressing a critical gap in prior assessments that focus narrowly on material efficiency without considering governance and land-use dimensions. This approach also aligns with the need for context-sensitive circularity metrics that compare productive areas and account for diverse agrifood system processes (Velasco-Muñoz et al., 2021).

A key advantage of these indicators is their ability to support cross-sector alignment. Stakeholders noted that framing results in terms of nutrients, rather than generic terms like "organic waste" or "fertilizers," can enhance alignment across sectors and minimizes fragmentation in policy and strategy development. Moreover, by distilling systemic findings into high-level, interpretable outputs, these indicators provide direct insights for both technical and non-technical audiences. For instance, quantifiable statements such as "X% of urban nutrients are recovered" (RUN) or "Y% of recovered nutrients are reused in agriculture" (RNA) offer a practical snapshot that can guide policy decisions and resource allocation.

These indicators directly align with key urban planning objectives in the Global South, such as waste reduction, pollution mitigation, and regenerative agricultural practices. Additionally, the scalability and comparability of these indicators make them valuable for benchmarking progress across regions, allowing urban planners to integrate nutrient circularity into broader sustainability strategies such as waste reduction, pollution control, and regenerative agriculture. By providing a unified and strategic framework, RUN and RNA indicators help bridge the gap between scientific assessments and policy implementation, making nutrient circularity a more tangible, operational and measurable goal rather than a conceptual goal.

3.5.6. Limitations and Future Work

The study faced several limitations, beginning with the inherent challenges of defining spatial and analytical boundaries. These boundaries may have excluded important activities, actors, and flows, particularly in light of the ongoing southward shift of agriculture to the O'Higgins region. Despite this risk, the strategic advantages of working within the Metropolitan Region of Santiago’s (MRSC) political and administrative boundaries were prioritized. Another challenge was classifying green areas, as their unique material inputs—such as mineral and organic fertilizers—differ from other essential flows within the Commerce and Consumption (CC) subsystem and align more closely with the Crop Production (CP) subsystem. This misalignment is further complicated by the lack of institutional oversight for green area fertilization, which

complicates strategy formulation and implementation. Additionally, the Sankey diagrams used to visualize nutrient flows have limitations due to the wide variation—ranging 3 to 4 orders of magnitude—among sectors, making comprehensive interpretation difficult. Assumptions were also necessary for flows with insufficient data, such as the use of compost and biofertilizers, though these were validated by local experts. The analysis did not distinguish between external and internal nutrient circularity, as this differentiation was not considered a priority for the context of the study. Finally, while further analysis could incorporate geographic characteristics and factors influencing actor behavior, such investigations are more valuable when applied to specific nutrient circularity strategies and projects.

Future research will utilize the diagnosis to identify gaps and opportunities within local nutrient management strategies, developing pathway narratives to address these challenges and enhance nutrient circularity in the MRSC. By integrating these diagnostic findings with existing policies and aligning them with stakeholder interests, the research aims to strengthen strategic planning efforts for urban sustainability, embedding nutrient circularity as a core component of future planning processes. Although the current study concentrated on material flow recovery and reuse, without a comprehensive assessment of regional nutrient circularity, future research will investigate systemic changes that extend beyond waste management. These efforts will include strategies to reduce the demand for fertilizers, animal feed, and food ingredients, thereby promoting a more sustainable and integrated approach to regional nutrient management.

3.6. Conclusion

This study underscores the necessity of a spatially and socially inclusive approach towards nutrient circularity strategies, aiming to enrich the discourse on sustainable urban and regional planning. In this study, actors within the agri-food-waste system emphasized the urgent need for improved territorial planning, recognizing its crucial role in promoting sustainable, circular development and resource management. The integration of urban metabolism and urban planning frameworks poses a complex and formidable challenge within the scientific community. Recognizing the intricate interplay between rural and urban landscapes, this approach acknowledges the dynamics of space, flows, and people. Moreover, this research aims to contribute to existing and future efforts by introducing a strategic, multi-dimensional diagnostic tool for assessing the management of nutrient resources from a territorial perspective. In future research, this diagnostic will be used to identify gaps and opportunities in local strategies, propose narrative pathways to address them, and evaluate the potential impact of such analyses for local planners, decision-makers, and other metropolitan areas in the region. Finally, this research shared an adaptable diagnostic methodology that addresses the need for a multidimensional approach to regional nutrient circularity strategies, allowing local planners to

identify key challenges and opportunities to inform their strategies, as well as to advance connections between urban and rural landscapes, as well as across sectoral and district boundaries.

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CRediT authorship contribution statement:
Alma Fleitas Girett: Conceptualization, data curation, formal analysis, methodology, investigation, writing – original draft, visualization, project administration. **Tom Wassenaar**: Supervision, formal analysis, visualization, validation, writing – review & editing. **Claudia Pabón Pereira**: Supervision, writing – review & editing.

Declaration of Competing Interest:
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process:
During the preparation of this work the authors used Chat GPT in order to proofread the article text for improved grammar and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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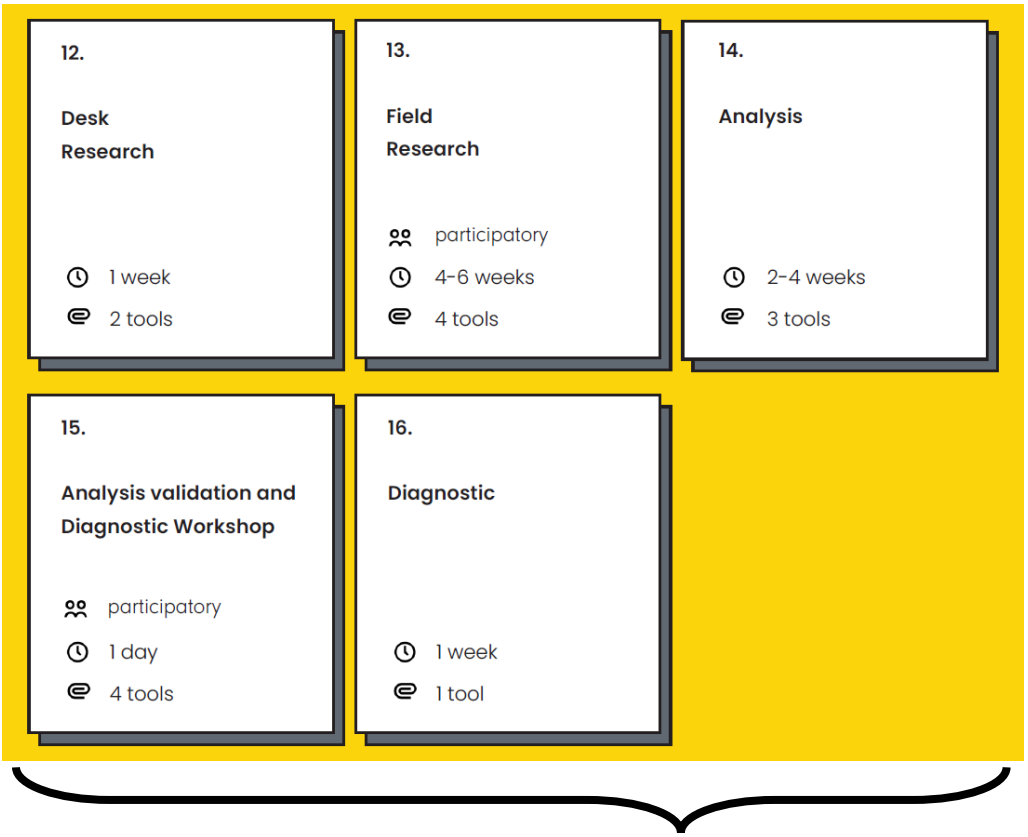
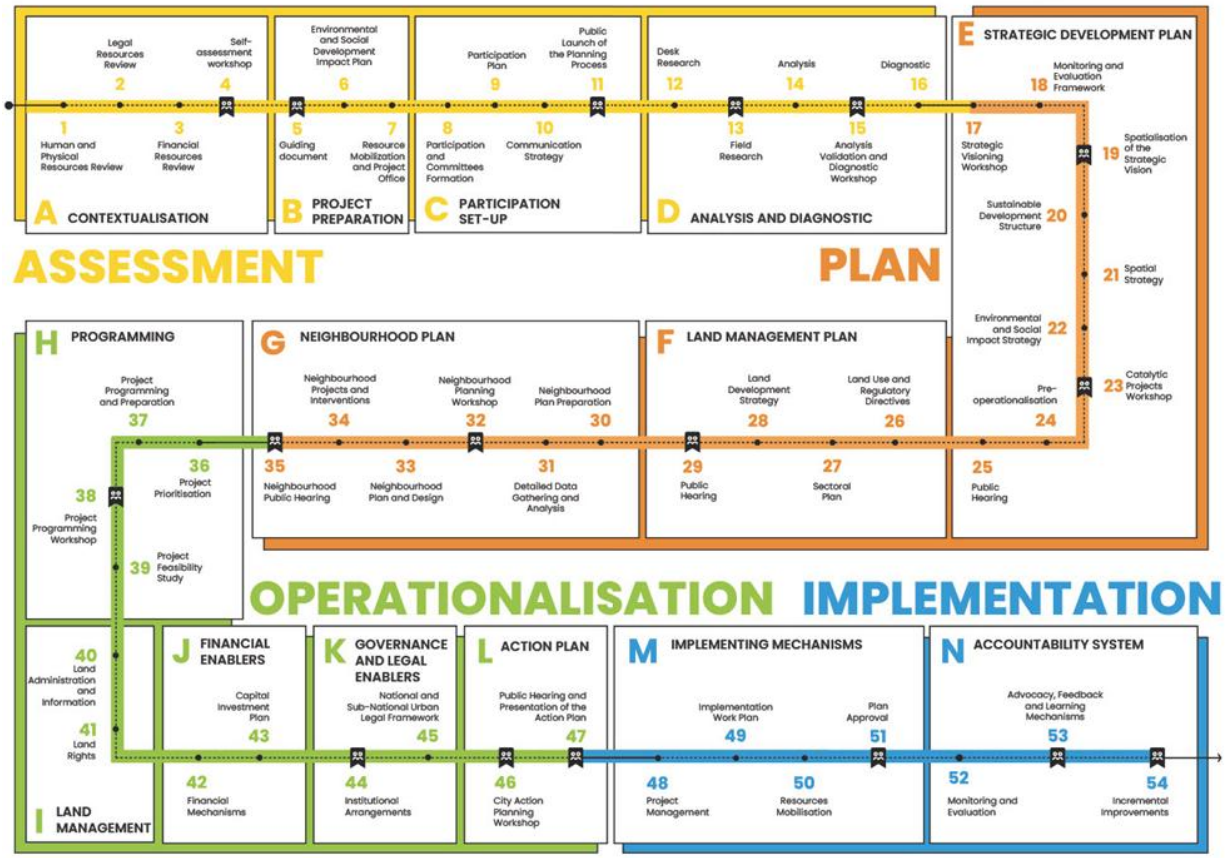
3.8. Appendices

A. Block D of the UN “Our City Plans" methodology (UN Habitat, 2022)





B. Interview guideline

Interview: Material Actors

Area of Interest	Question	Details
Introduction / Role	Organization (Vision, goal, activities) You (background, role, tasks)	General info
	How does your organization engage with nutrient flows?	Producer, Transformer, Utilizer, Collector, Promoter, Organizer, Regulators, Problem Solvers
Material Flows	What kind on nutrient-containing products are used as input for your processes? How much? Where is it from? Why is that product used?	How stable is the availability of these input products? Awareness, ease of use, efficiency, cost of organic / compost products?
	What kind of nutrient-containing waste or by-products are produced from your processes? How much? Where does it go? Why does it go there?	If it's receiving special treatment, what technology is being used? Is that technology accessible / efficient / are there enough people who know how to operate it? Info about the end product of such treatment (demand, feasibility, usability, etc.).
	Are you satisfied with how these flows are being managed?	If not satisfied, why?
Sectoral Characteristics	What kind of platforms exist to work/engage/exchange with other producers and relevant stakeholders?	What are the main goals of these spaces?
	How feasible is it to switch to more circular models / products?	Costs, materials, capacity (opportunities, barriers)
	Are you aware of goals and commitments that exist within the sector regarding sustainable nutrient use and/or recovery? Existing projects?	How are these goals or commitments being monitored and reported?
Knowledge Base	Do actors within the sector share information regarding input and output materials, circular practices and business models, etc.?	To whom? Where/How? Do you use the information?
	Are you aware of, carrying out, or part of research in these areas? Pilot projects?	Why are you doing this? What info is missing?
Institutional Foundation	Are you aware of relevant national or local policies regarding nutrient circularity?	How do they affect producers within the sector?
	What institutional roles and functions are necessary to support the sector in these matters?	What institutions or organization do you engage with? Why? Are they fulfilling your needs?
	How do environmental standards and regulations (that apply to nutrient circularity) affect the sector?	
Proposals / Comments	How can higher nutrient circularity be achieved within the sector?	What are the main barriers to this? What should be prioritized? New tools / instruments
	Who is another key actor that should be included in this study?	

Interview: Influential Actors

Area of Interest	Question	Details
Introduction / Role	Organization (Vision, goal, activities) You (background, role, tasks)	General info
	How does your organization engage with nutrient flows?	Producer, Transformer, Utilizer, Collector, Promoter, Organizer, Regulators, Problem Solvers
Material Flows	What nutrient flows are of greatest importance to you / your organization in the RMSC (in terms of quantity, quality)?	Origin, destination, impact
	What kind of treatment options are best for managing these flows, and why?	Availability, feasibility, end product, nutrient recovery potential
	Are you satisfied with how these flows are being managed?	If not satisfied, why?
Sectoral Characteristics	What kind of consumer values and practices exist regarding these flows?	Acceptance, demand, awareness, pressure
	How much cooperation occurs between actors of the relevant sectors? (Agriculture, Food processing, Commerce & Consumption, Waste Management)	Roundtables, material exchange platforms, data sharing
	Are businesses from these sectors interested in switching to circular models/products?	Why are they switching? How feasible is it for businesses to make that transition?
Knowledge Base	What kind of information does your organization generate and/or manage regarding nutrient flows?	Is it shared? How, and to whom?
	Does your organization dedicate resources for R&D regarding nutrient circularity topics?	Examples of projects, research areas, pilots, etc.
Institutional Foundation	How does (or can) your organization support nutrient circularity initiatives / strategies?	What policies are lacking / lagging?
	Who within your organization works on these initiatives / strategies / policies?	What's their background? Are these certain skills or resources that are needed to increase the institutions capacities in these areas?
	How do environmental regulations affect nutrient circularity strategies / policies?	
Proposals / Comments	How can higher nutrient circularity be achieved within the sector?	What are the main barriers to this? What should be prioritized?
	Who is another key actor that should be included in this study?	Organization, contact person

C. NPK Quantification

Dimension	Data inputs	Suggested Data Sources
Space	Administrative boundaries	Public GIS database
	Land use	Public GIS database
	CP: locations of individual farms; district-level cropland per crop type; agricultural land use	Public GIS database; PRTR database; agricultural census data; national statistical or sectoral database;
	AP: location of individual farms; district-level animal population shares	Public GIS database; PRTR database; agricultural census data; national statistical or sectoral database
	FP: location of individual industrial plants	PRTR database
	CC: locations of individual commercial establishments (e.g., supermarkets); district-level population density; urban/built-up area land use; public green area land use	PRTR database; national statistical database; public GIS database
	TR: locations of individual treatment & recycling facilities (ex. WWTP)	PRTR database; public GIS database
Flows	CP inputs: Surface area per crop type; nutrient demand (t/y) per hectare per crop type; yield per crop type; fertilizer nutrient content; fertilizer application rates per crop type; Quantity of nutrient-containing waste (t/y) destined for CP (e.g. sludge from TR or FP, swine manure from AP); nutrient content from per material & activity;	Agricultural census data, local publications, technical reports, fertilizer product information; agricultural technical manuals; PRTR database
	CP outputs: Fertilizer volatilization rates; yield loss per crop type; tree pruning waste rates; crop waste nutrient content; fates of crop waste (e.g., % burned, to animal feed, etc.)	National Inventory Report of GHG Emissions; local publications; technical reports; scientific literature
	AP inputs: Animal population data per animal type, detailed as possible (e.g., broiler chicken, layer chicken, sows, etc.); feed consumption rates per animal type; feed nutrient content; Quantity of nutrient-containing waste (t/y) destined for CP (e.g. byproducts from FP); nutrient content from per material & activity;	Agricultural census data; local publications; technical reports; scientific literature;
	AP outputs: Animal population data per animal type; animal excretion factors; volatilization rates based on local manure management; fate of animal waste (% to rendering, environment, etc.)	Agricultural census data; National Inventory Report of GHG Emissions; local publications; technical reports; scientific literature;
	FP outputs: Quantity of nutrient-containing waste (t/y) generated according to fate type (landfill, TR, AP); nutrient content per material & activity	PRTR database;
	CC outputs: 1) Household organic solid waste generation rates (differentiating garden and food waste); population; organic recycling rate, 2) Human excreta	1) National statistical database; local publications; technical reports; scientific literature; 2) previous +

	rates; wastewater nutrient content; fate of nutrients (% to WWTP, landfills); 3) Commercial waste (t/y) generated (e.g., supermarkets, open markets); nutrient content of commercial waste materials; fates of commercial waste (% to landfills, WWTP); 4) Green area surface area; green area waste generation rate; green waste nutrient content; fate of green waste (% to composting, landfills)	FAO country diet data; PRTR database; 3) PRTR database; local publications; technical reports; scientific literature; 4) public GIS database; local publications; technical reports; scientific literature;
	TR inputs: Quantity of nutrient-containing waste (t/y) destined for TR activities (WWTP, composting plants, etc.); nutrient content per material & activity (e.g., sludge from the dairy industry)	PRTR database; local publications; technical reports; scientific literature;
	TR outputs: Quantity of nutrient-containing outputs (t/y) (e.g., sludge, compost); emission rates based on treatment type; nutrient content per material & activity; fate of outputs (% to CP, AP, environment)	PRTR database; local publications; technical reports; scientific literature;
People	Stakeholder groups/names (public, private, civil sectors)	Main relevant national or regional policy documents and plans; interview responses
	Stakeholder role type categorized as organizational, material, or both; roles defined based on Bijon et al. (2023)	Interview responses, official organization websites and documents
	Stakeholder main priority: recovery of urban nutrients (RUN) or the reuse of nutrients in agriculture (RNA)	Interview responses, official organization websites and documents
	Existence of interactions between stakeholders ('Do these two actors regularly and significantly interact or collaborate on managing key flows?' - yes/no) & interaction types (organizational, material, or both)	Interview responses, official organization websites and documents

Crop Production:

Fertilizer demand was based on crop surface area from the 2021 Agricultural Survey, yield from local publications, in addition to fertilizer nutrient content and recommended fertilizer application rate from local technical manuals from agricultural institutions. Though only the “top crops” were used for this initial calculation (crops accounting for 50% or more of the surface area per crop group), this value was then extrapolated to account for all crop land for its crop group. The volatilization of nitrogen in fertilizers was also considered based on rates presented in Chile’s 2021 National Inventory Report of Greenhouse Gas emissions. Nutrient input calculations from animal excretions are explained in the following section. The use of bioinputs such as organic fertilizer and soil amendments could not be calculated due to lack of data. Crop waste was also calculated considering crop surface area and yield, as well as yield loss and pruning waste rates acquired from local technical publications, depending on the type of crop. This was then multiplied by the crop’s waste nutrient content acquired from a combination of local publications and scientific literature. Subsequently, nutrient destination was also calculated considering different fate option and rates presented in local technical publications.

Animal Production:

AP output flows were calculated using animal population data from the 2020 Agricultural Census (source) at municipal level. For poultry we considered only total populations for two categories: broiler chicken and layer hens. For pigs we separately assessed output flows of three subcategories: sows, finisher pigs and fattening pigs (from weaning up to finishing). The identification of animal farm owning holdings in the Census, combined with the identification of large industrial holdings in the RETC database, allowed assigning municipal population shares to the latter holding type. Nitrogen output flows were calculated using excretion factors as well as factors for direct N2O emission and N volatilization from manure management as provided by Chile's 2021 National Inventory Report of Greenhouse Gas Emissions (source). The fairly standardized monogastric production and manure management allow for the use of such national level factors. Only the broiler manure management N volatilization was upwards adjusted following expert reports on the regionally common practice of active windrow aeration before land application. Phosphorus and potassium output flows of each population and category were assessed on the basis of their ratios with N excretion as reported for similar production systems ("standard" feeding) by the French Steering Committee for Environmentally Friendly Agricultural Practices (CORPEN).

Nutrient intake of each animal population and category was assessed as both a means to validate output flow estimates and to appreciate the level of (feed) import dependence of the RMS region. We assessed pig intake on the basis of dry weight feed intake per category as reported by Chile's National Inventory Report of Greenhouse Gas Emissions and applied nitrogen and phosphorus concentrations as reported for European Union member states with similar feed consumption ratios by Sebek et al. (2014). We estimated broiler chicken and layer hen intake on the basis of feed consumption and feed concentration values reported by Sebek et al. Potassium concentration estimates were based on secondary feed formulation data from the feed industry and from CORPEN and information from the International Plant Nutrition Institute (1998).

Food & Feed Processing:

Only outputs were calculated, based on flow analysis scope. Volume of waste generated per activity was gathered from the PRTR database and then multiplied by nutrient content per waste type. Additionally, nutrient fate was estimated using the respective destination types listed in the PRTR database.

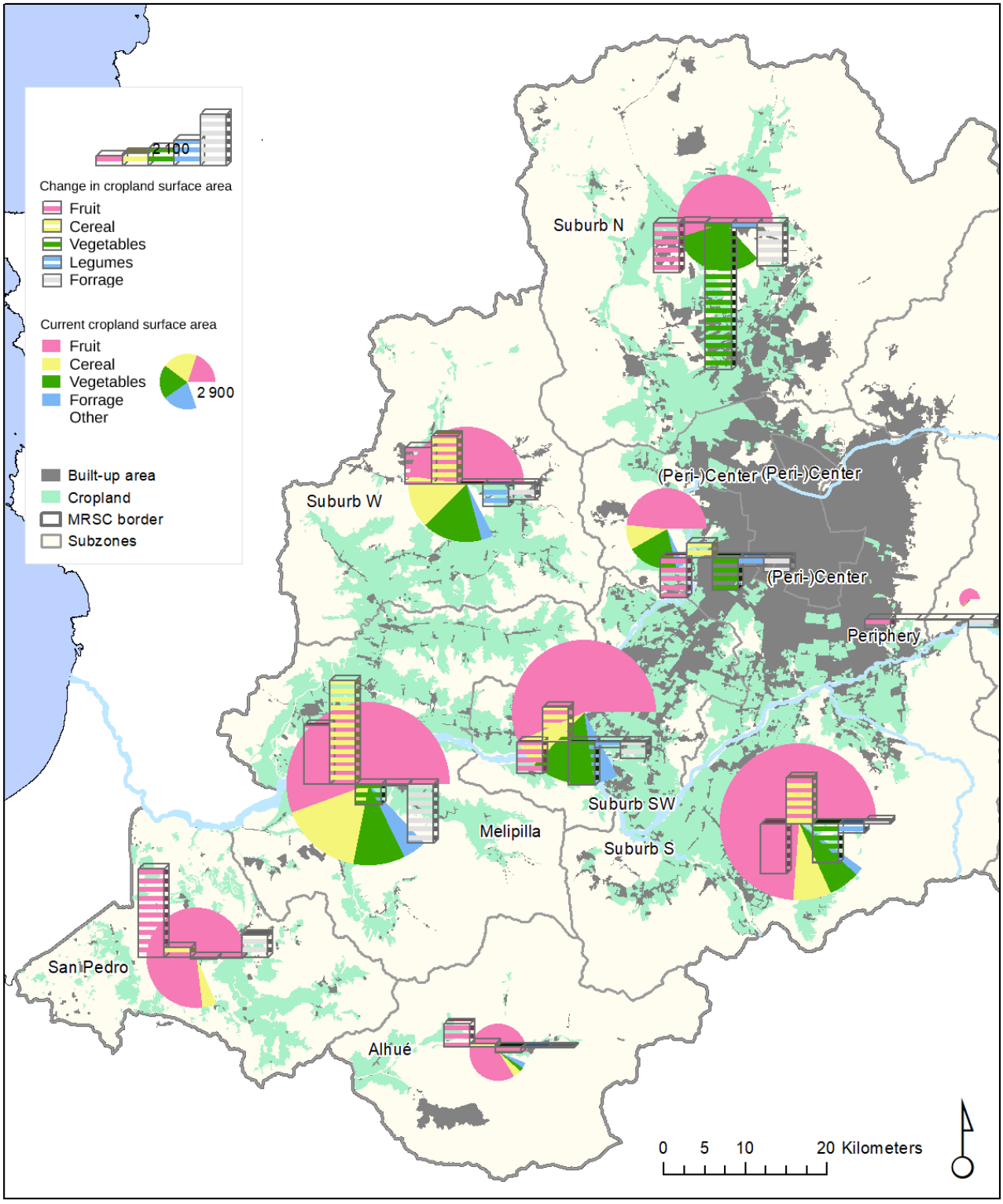
Commerce & Consumption:

Similarly to FP, only output flows were quantified for the four main activities: households, supermarkets, open markets, and green areas. Household waste generation was split into solid waste, made up of food and garden waste, and wastewater. Solid waste was calculated using population, generation rate, and municipal waste composition. Fate of solid waste was estimated using recycling rates indicated in local publications. Nutrient content in wastewater was calculated using population data and nutrient content of human excreta based on literature and FAO data specific for local diet. Again, fate of nutrients was calculated using information from local publications. Supermarket and open market outputs were calculated using PRTR data, multiplied by nutrient content per waste type, and then estimated for different fates provided in the same database. Finally, green area outputs were calculated using surface area and green area waste generation rate obtained from scientific literature.

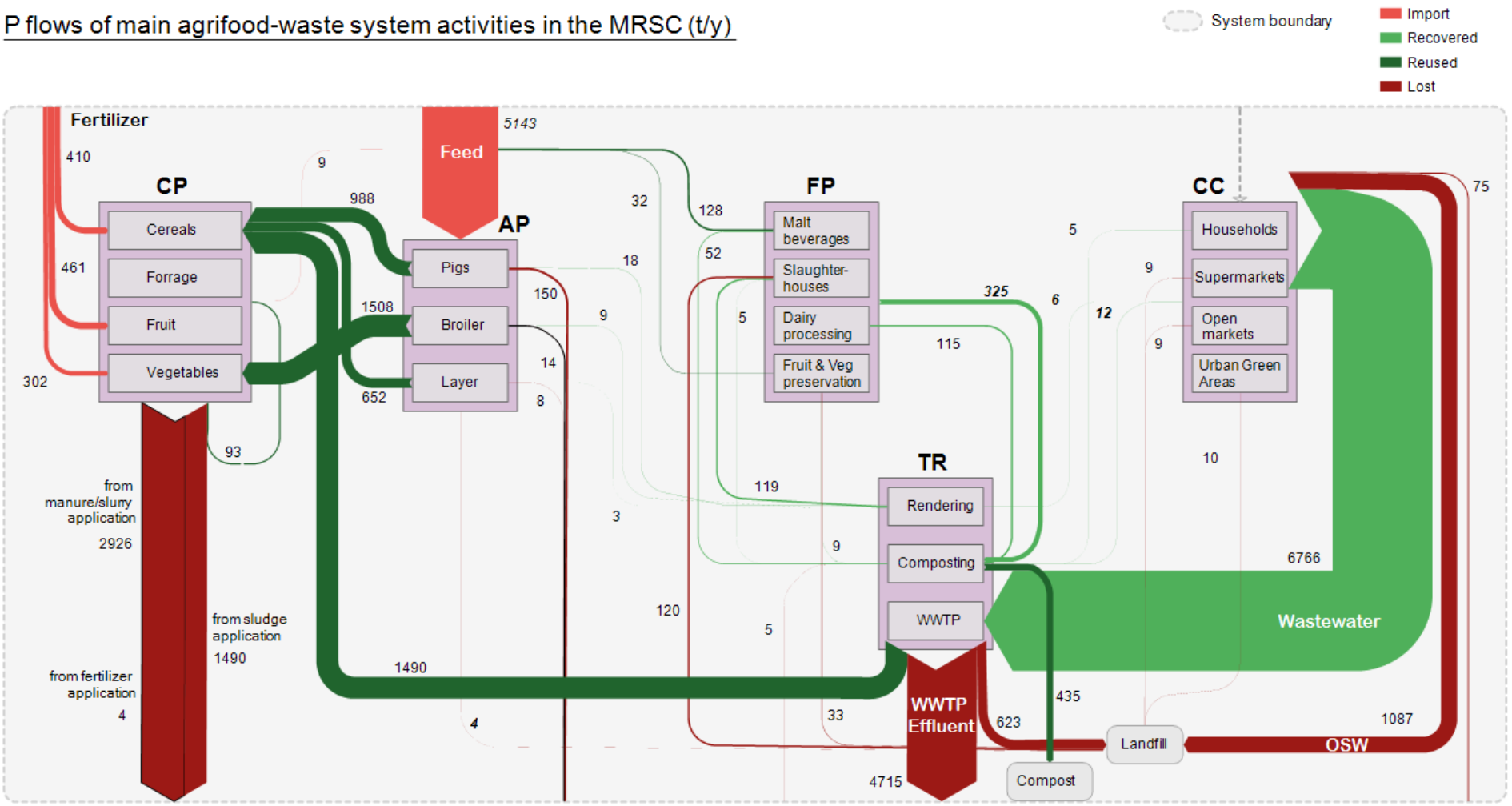
Waste Treatment & Recycling:

Inputs to waste treatment and recycling were calculated based on output quantities from AP, FP and CC activities described in the previous sections. WWTP outputs were calculated using PRTR data of sludge generation, nutrient content and destination based on local sources. Composting industry outputs were estimated using compost generation rate from a local publication and nutrient content based on scientific literature from the region. No other organic fertilizers or bio-inputs were calculated due to lack of data.

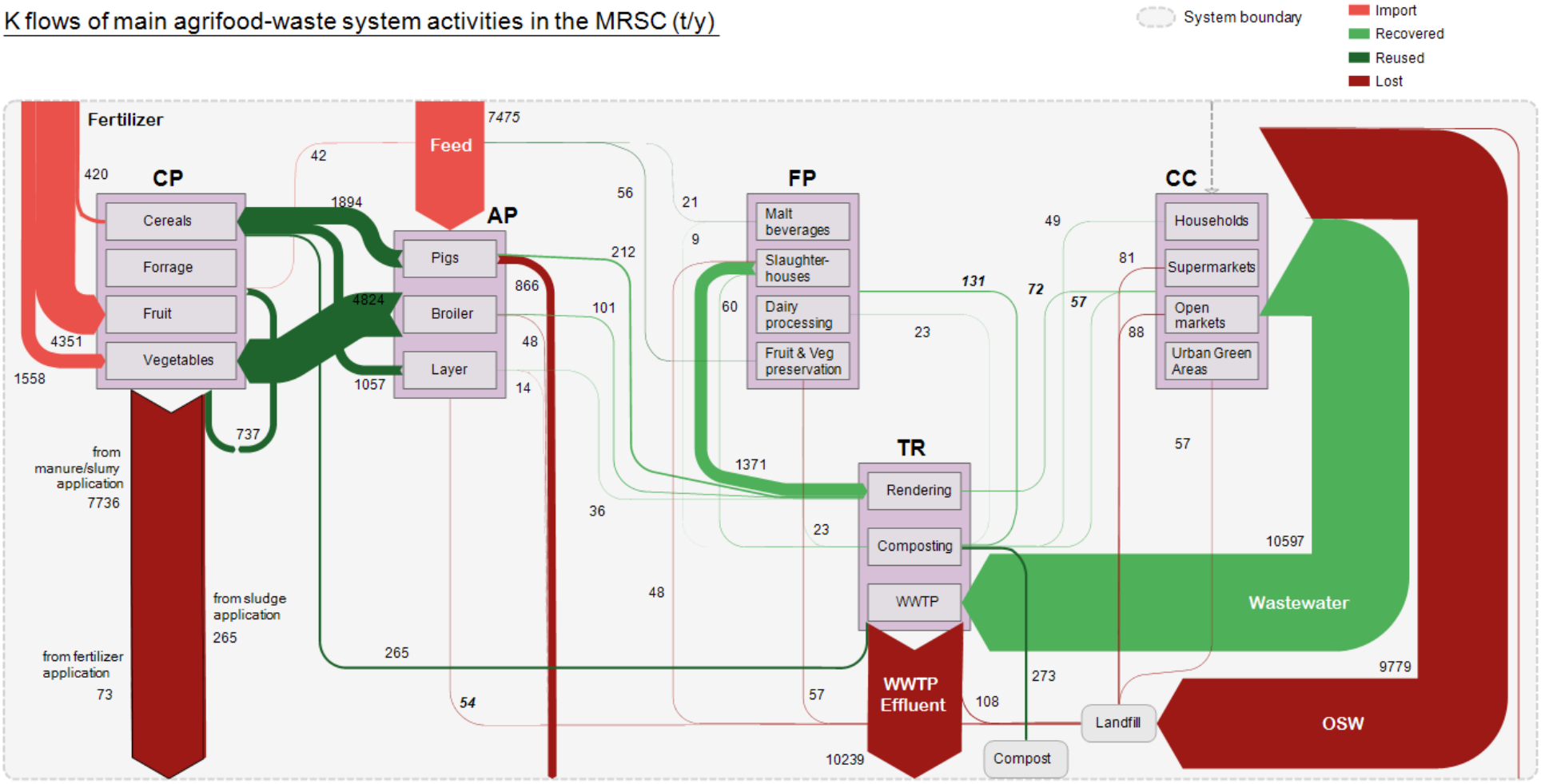
D. Map of current and change in cropland use by crop type (2016 – 2021)



E. Detailed Sankey diagrams of P and K flows in the MRSC



K flows of main agrifood-waste system activities in the MRSC (t/y)



F. Summary of MRSC Material Flow Analysis

Nutrient Demand:

The metropolitan region contains a diverse range of crop types, each with varying nutrient demands and types of input products. Urea application emerges as a primary input for all crops, especially cereals and vegetables, which typically receive higher dosages compared to fruit trees. Fruit trees, on the other hand, are commonly supplemented with potassium fertilizers, while phosphorus application tends to be lower. Cereals and vegetables may also receive NPK mix products to meet their nutrient requirements. However, there is a notable lack of data regarding the utilization of bio-inputs in agriculture, such as compost and organic fertilizers. While interviews revealed a preference for bio-inputs in managing urban green areas, the absence of data on their application, combined with inconsistent management practices, impeded the calculation of this demand flow.

Similarly, obtaining local animal feed data proved challenging. As is explained in Appendix C, the animal feed sector's demand is not specified at the elemental level but rather at the molecular level or higher. Sectors such as Food Processing and Rendering, potentially capable of supplying such materials, are already doing so. Interviews indicated a heavy reliance on imported soy, maize, and wheat products, alongside the incorporation of additives obtained from rendering plants as secondary materials. However, quantifying this flow necessitated a theoretical approach based on animal populations.

Nutrient Supply and Losses:

CP and AP primarily generate raw crop waste or minimally processed animal slurry, while FP produces both raw waste streams containing solid waste and processed outputs such as sludge. TR releases processed materials, including treated water and compost, due to their role in processing and refining waste flows. CC activities produce raw materials such as organic solid waste, garden waste, and wastewater. Nutrient losses occur through various channels, including domestic organic solid waste, effluents, and emissions from wastewater treatment plants, as well as from crop production. Interviews with local agricultural experts reveal that farmers often overlook nutrient supply considerations when applying pig slurry, layer manure, and sewage sludge to cereal croplands, leading to an accumulation of excess nutrients and subsequent environmental losses. Similarly, broiler manure application in vegetable production exacerbates this issue, deterring nutrient circularity in the region.

Spatial analysis indicates that nutrient excesses are not uniform across all MRSC zones (Figures 12 a, b, c). Zones with few animal farms, such as Suburb S, are proximate to areas saturated with nutrients, like San Pedro, due to the concentration of AP activities in the region. Although Suburbs S and N contain TR activities that could provide secondary products like sludge or organic fertilizers, current regulations restrict such applications. Interviews with local stakeholders further reveal that the crop sector with the highest nutrient demand, particularly fruit production for export, receives minimal recovered nutrients, despite being located in areas with high nutrient surpluses.

Byproducts from FP are likely recovered through composting and rendering activities, but losses likely occur to the environment that are currently difficult to assess. N losses predominantly occur towards the atmosphere, whereas P is lost through treated water discharge from wastewater treatment plants, contributing to eutrophication of water bodies. Similarly, unquantified treated wastewater discharge from FP industries like Malt beverages and Dairy processing further contributes to water body eutrophication. Regarding K, significant losses occur from households to landfills through municipal solid waste, with the majority lost through treated water discharge and excess application to vegetables and cereals, likely draining into groundwater. Rendering recycles a significant portion of K into unknown products, while very little ends up in compost. Overall, water and landfills are the main fates of K.

Nutrient Balances:

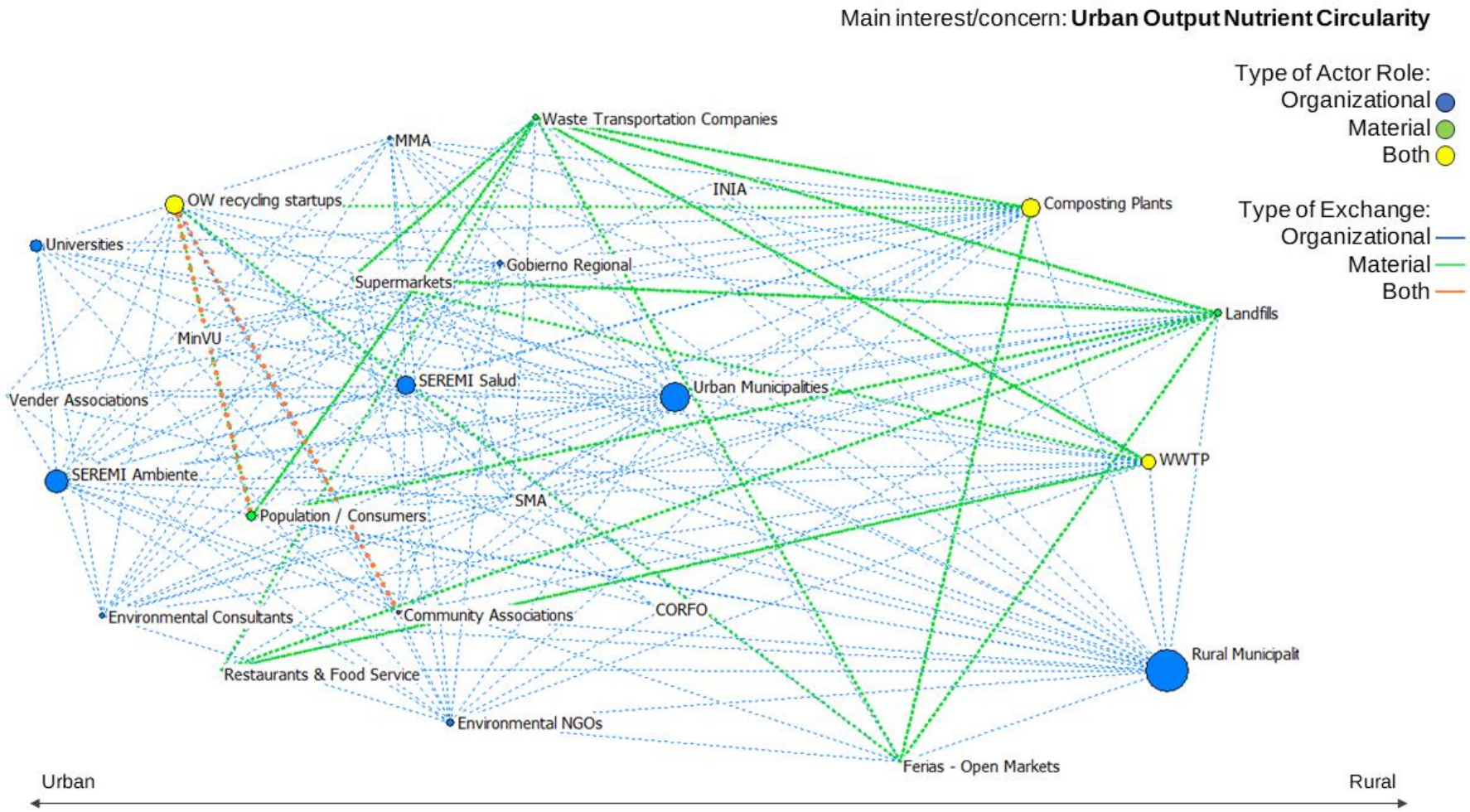
In the MRSC, households (CC) are the primary source of nutrients, contributing to a significant surplus of nitrogen to the system. The N surplus exceeds demand/imports by over fivefold, with over 53 thousand tons generated yearly as compared to around 10 thousand tons imported to CP and AP. Similarly, there is a significant excess production of phosphorus and potassium, with households generating

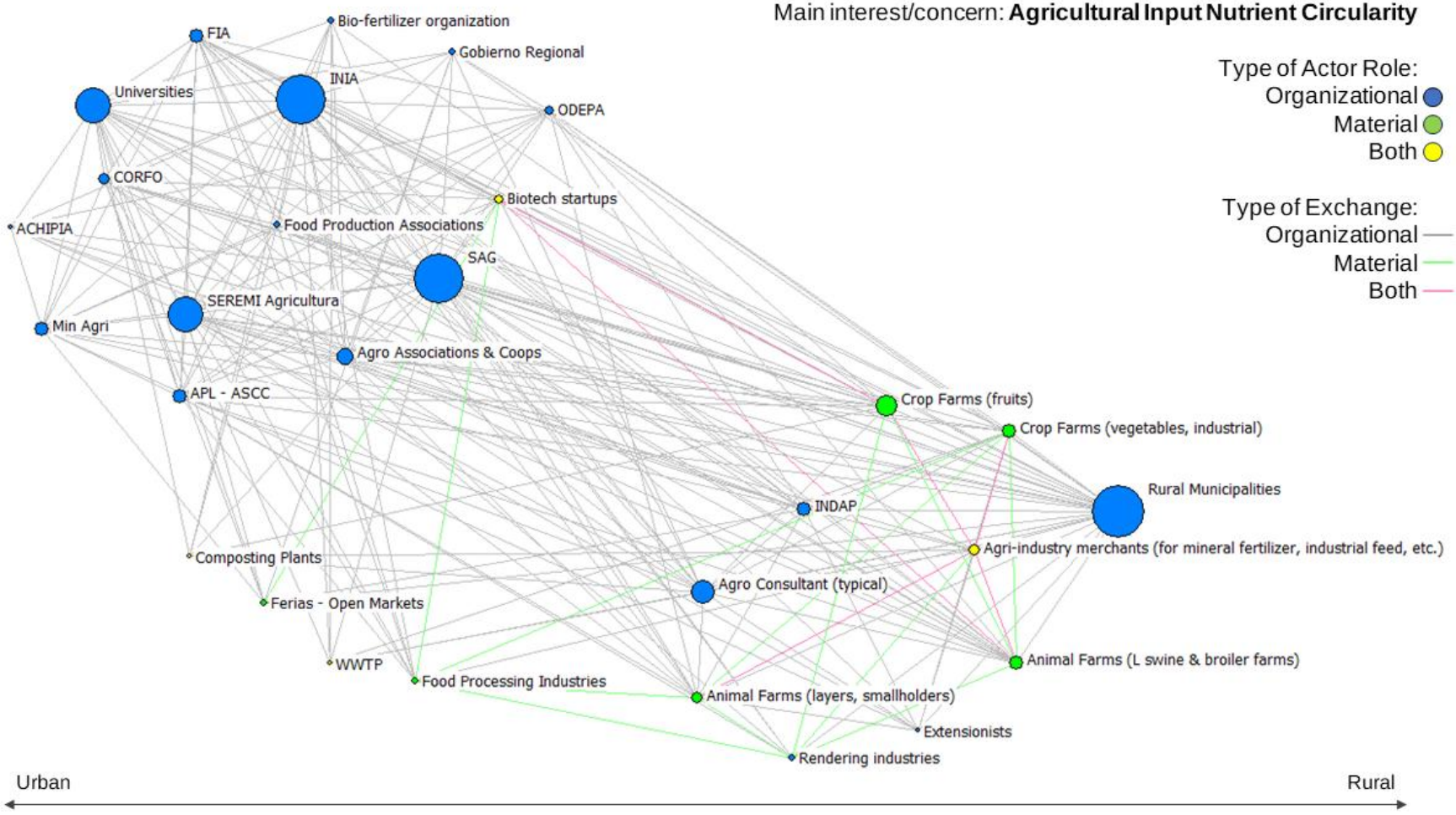
approximately six times (nearly 8 thousand tons) and three times (about 20 thousand tons) the imported quantities, respectively. However, when factoring in the theoretical nutrient imports for animal feed, the surplus diminishes: nitrogen generation almost matches demand by a factor of 1.4, while phosphorus and potassium show surpluses exceeding demand by 1.3 and 2 times, respectively.

In summary, the MRSC functions as a large NPK sink. NPK resources are primarily used once, with minor reuse from FP byproducts to AP feed and through assumed Rendering and Composting products, such as blood meal and organic fertilizers. However, even without considering application rates and mineral fertilizer substitution, current material flows to crops would not adequately meet their nutritional requirements. For example, tailoring manure or sludge application to meet cereal N demand would lead to excess P. In addition to atmospheric losses, environmental loss estimates often rely on input-output differences, which can sometimes be substantial. It's essential to validate these estimates using local measurements whenever possible, and to contemplate different management and technological options to increase nutrient recovery and reuse in the region.

The MRSC closely overlaps with the Maipo River basin, where data from river measurements provide insights into phosphorus content. These measurements indicate that upstream concentrations are minimal, indicating a primarily local, anthropogenic origin. By combining the average observed P content near the MRSC outlet (0.5 mg/L) with the mean annual discharge (123 m^3/s), we estimate that the basin discharge accounts for approximately one-third of the phosphorus discharge from wastewater treatment plants. This finding confirms the scale of our estimate and further suggests that P applied to soil from waste tends to remain stored there. Moreover, the data suggest that a significant portion of P discharged from WWTPs is unknowingly applied to crops through irrigation, as low discharge rates resulting from excessive pumping for irrigation have been documented (Lagos del Río, F. A., 2023).

G. Social network diagrams




Main interest/concern: **Agricultural Input Nutrient Circularity**
Type of Actor Role:
Organizational
Material
Both
Type of Exchange:
Organizational
Material
Both
FIA
Bio-fertilizer organization
Gobierno Regional
Universities
INIA
ODEPA
CORFO
Biotech startups
ACHIPIA
Food Production Associations
SAG
SEREMI Agricultura
Min Agri
Agro Associations & Coops
APL - ASCC
Crop Farms (fruits)
Crop Farms (vegetables, industrial)
Rural Municipalities
INDAP
Agri-industry merchants (for mineral fertilizer, industrial feed, etc.)
Composting Plants
Agro Consultant (typical)
Ferias - Open Markets
Animal Farms (L swine & broiler farms)
WWTP
Food Processing Industries
Animal Farms (layers, smallholders)
Extensionists
Rendering industries
Urban
Rural

In the third step toward incorporating nutrient circularity into ongoing or future strategic planning processes, it is essential to integrate and synthesize the diagnostic findings with existing policies, strategies, and stakeholder interests and concerns. This requires once again linking urban metabolism and urban planning tools to provide outputs that offer stakeholders and planners a systemic and circular perspective on managing nutrient-containing flows. Additionally, it is vital to present the synthesis outcomes— strategically organized overlaps and gaps—in a way that is effective, accessible, and functional for stakeholders to explore potential futures for their territory.

4. **INCORPORATING NUTRIENT CIRCULARITY INTO STRATEGIC URBAN PLANNING:** FROM DIAGNOSIS TO SCENARIO NARRATIVES FOR THE METROPOLITAN REGION OF SANTIAGO

4.1. Introduction

In response to climate change and urbanization challenges, cities and metropolitan areas around the world are actively incorporating sustainability principles into their urban planning (Domenech and Borrion 2022). Many countries have committed to the United Nations' Sustainable Development Goals, and in recent years, have been incorporating these goals into national and regional development plans (Chimhowu et al. 2019). In adopting these goals, cities and regions are in the process of developing strategic visions and roadmaps focused on sustainable resource use (UNIDO / Chatham House 2024). This also fosters for the incorporation of popular, relevant agendas like circular economy and bioeconomy, especially in response to SDG 11 'Sustainable Cities and Communities' and SDG 12 'Responsible Consumption and Production', both of which involve sustainably managing material flows within territories (Ellen MacArthur Foundation 2019). These development plans and roadmaps are often constructed through strategic urban planning. Strategic urban planning is a iterative process, aiming for incremental improvement through adaptive processes that incorporate reassessments, feedback, and refinement, which can be subdivided for consistency into four stages: assessment, planning, operationalization, and implementation (UN Habitat 2022). In the context of urban sustainable development, a top research priority is the sustainable use of resources. In natural science research, these objectives are often studied in terms of urban metabolism and circular resource management. Tools like the Material Flow Analysis have been very valuable for evaluating resource management at a territorial level, aiming to provide critical insights for policy and planning processes. For many cities around the world, organic or biological materials are a priority, spanning across issues from municipal waste management to food security and agrifood system resilience (Rosemarin et al. 2020; Cabannes, Y. and Marocchino, C. 2018). To address these challenges, nutrient circularity strategies are crucial for achieving sustainable territorial development, requiring comprehensive and systemic approaches (van der Wiel et al. 2021; Spiller et al. 2023; Stamm et al. 2022).

Research, particularly from the field of urban metabolism (UM), has made progress in adopting planning principles and tools, increasingly considering spatial and social variables on top of environmental ones. Traditionally, researchers have mostly focused on the first part of the planning process, that is, Assessment, which results in diagnoses that provide insights into priority areas, opportunities and challenges for the territory. Therefore, research regarding urban metabolism diagnostics has expanded beyond material flow accounting to include social, economic, and spatial information in their analyses (Amenta et al. 2022). Regarding nutrient-containing material flows, notable examples of planning-oriented research include the works of (Wielemaker 2019; REPAiR Project 2018; Arciniegas et al. 2019), among others who

have integrated multiple dimensions of data for more comprehensive analysis. These findings are vital for creating alternative scenarios that allow the exploration of possible futures, which is the first step of the second phase, *Planning*.

The linking of the Assessment and Planning phases is crucial, some UM-focused research has gone beyond the diagnostic phase and included planning steps into their research, typically emphasizing scenario modeling and simulations to generate quantitative findings (Kennedy et al. 2011). Examples related to nutrient circularity include (Taffuri et al. 2021; van Selm et al. 2024; Papangelou et al. 2020; Vanhamäki et al. 2020), with outcomes ranging from quantitative scenario studies to strategic roadmap development.

Considering the variety of materials and processes that occur within a territory, planning processes in the context of regional circular development need to consider a wide variety of perspectives throughout all the phases of planning. Currently, urban and regional planning processes are still lacking the perspective of nutrient circularity (Teleshkan et al. 2024; McGreevy et al. 2022). Instead, they typically deal with nutrient-containing flows through fragmented approaches, usually divided into rural / agricultural and urban / waste management strategies with separate actors and strategies (Tamsma et al. 2024; Bremmer et al. 2020). The previous severely limits the comprehensiveness and practical application of the scenarios to be drawn. Urban metabolism has made progress in considering nutrients with more systemic approaches, yet integrating these tools and outcomes into planning remains limited and delayed. As a result, current circular city agendas often rely on business-based circular economy models or existing legislative agendas (for example, regarding the recycling of waste), which are often not insufficient to address urban challenges complexities and can result in a limited diversity and disarticulation of solutions (Marjanović et al. 2022; Schöggl et al. 2020; Marin and Meulder 2018). The many causes contributing to this gap, range from a failure to consider the diverse factors that influence nutrient-flow management, a lack of or insufficient stakeholder involvement, disconnection from existing priorities and planning, among others (Korhonen et al. 2018; Oliveira and Vaz 2021).

In our previous work, we have attempted to address this knowledge and methodological gap by proposing a framework to develop a diagnosis of nutrient-flow management that is both multi-dimensional and strategic, aiming to produce insights valuable for planning processes. In this work, we go one step further, aiming to bridge the gap between the phases of Assessment and Planning (UN Habitat 2022), i.e. between a territorial nutrient-flow diagnosis to scenario building through the development of **narratives**. We propose a framework that integrates diagnosis insights with stakeholder inputs and local strategies to construct these narratives, providing an evidence-based and contextualized nutrient-circularity perspective for current and future scenario-building processes and vision exploration exercises that occur in

the context of circular urban development. Like the previous diagnostic framework, we have applied these tools to the Metropolitan Region of Santiago, previously found to be a regional leader in nutrient circularity capacity (Fleitas Girett et al. 2023).

4.2. Background

4.2.1. Strategic Urban Planning

To streamline the adaptation of research outcomes into planning processes, this research is based on the planning framework outlined in the UN's "Our City Plans" toolbox (UN Habitat 2022). Developed and utilized by UN-Habitat, this participatory and adaptable approach created by a multidisciplinary, international team, was designed for guiding planning processes towards sustainable urban development. The framework consolidates leading planning tools, best practices, and methodologies used in strategic planning processes, making them easily accessible to city leaders, planners, and other urban stakeholders. It has been successfully employed to develop municipal plans and guide planning exercises in several Latin American cities, including those in the countries of Brazil, Argentina, and Mexico.

The framework is organized in four phases: Assessment, Planning, Operationalization, and Implementation, each consisting of multiple blocks with varying outcomes (see **Figure 1**).



Figure 1. Summary of the "Our City Plans" Strategic Planning Framework (UN Habitat 2022).

Figure 1 This research is particularly concerned with the first two phases and the harmonization of their content for achieving synchronicity:

- Phase 1 – Assessment: It concludes with a diagnostic report that communicates the strengths, weaknesses, constraints and opportunities of the current situation.
- Phase 2 – Planning: It begins with scenario building, which uses qualitative and quantitative tools to describe possible futures and work towards building a strategic development and spatial plan.

Our previous work focused on the diagnostic step, proposing a multidimensional strategic framework to comprehensively assess the management of nutrient-containing flows on a regional scale. The main principles of this diagnostic framework are summarized in the following section. The subsequent section focuses on the core theories of scenario-building applied to this research to create a cohesive link between the Assessment and Planning phases of Strategic Urban Planning.

4.2.2. Urban Diagnostic

In our previous work, we aimed at developing a strategic multi-dimensional diagnostic framework designed for real-world application in strategic urban planning processes. **Figure 2** summarizes the theoretical framework that informed the development of this diagnosis, integrating urban planning and urban metabolism concepts, principles, methods, tools, and factors to assess nutrient-containing flow management. Following the UN planning framework mentioned above, our diagnosis process involved extensive stakeholder engagement, desk research, and literature review to collect and analyze data. This tool aims to provide insights to identify key priorities, opportunities, and challenges in the studied area; it consists of three main steps:

1) Defining the system scope and analytical boundaries,
2) Conducting a multi-dimensional analysis that included spatial, material flow, and social data, and
3) Integrating the analysis results into circularity indicators and visualizations.

When applied to the Metropolitan Region of Santiago, this diagnostic approach enabled the identification of key activities and nutrient-containing flows, their locations, distribution, trajectories, nutrient content, and the actors most concerned or connected to them. Additionally, this information revealed spatial opportunities and challenges, activities and areas of nutrient accumulation, losses, or recovery potential, and the extent of connection (or lack thereof) between key actors and priority activities and flows. According to the "Our City Plans" framework, diagnostic results should be summarized into a report and shared with relevant local stakeholders, often through public communication channels. It does not specify though how these results should feed into the subsequent “Planning” phase.

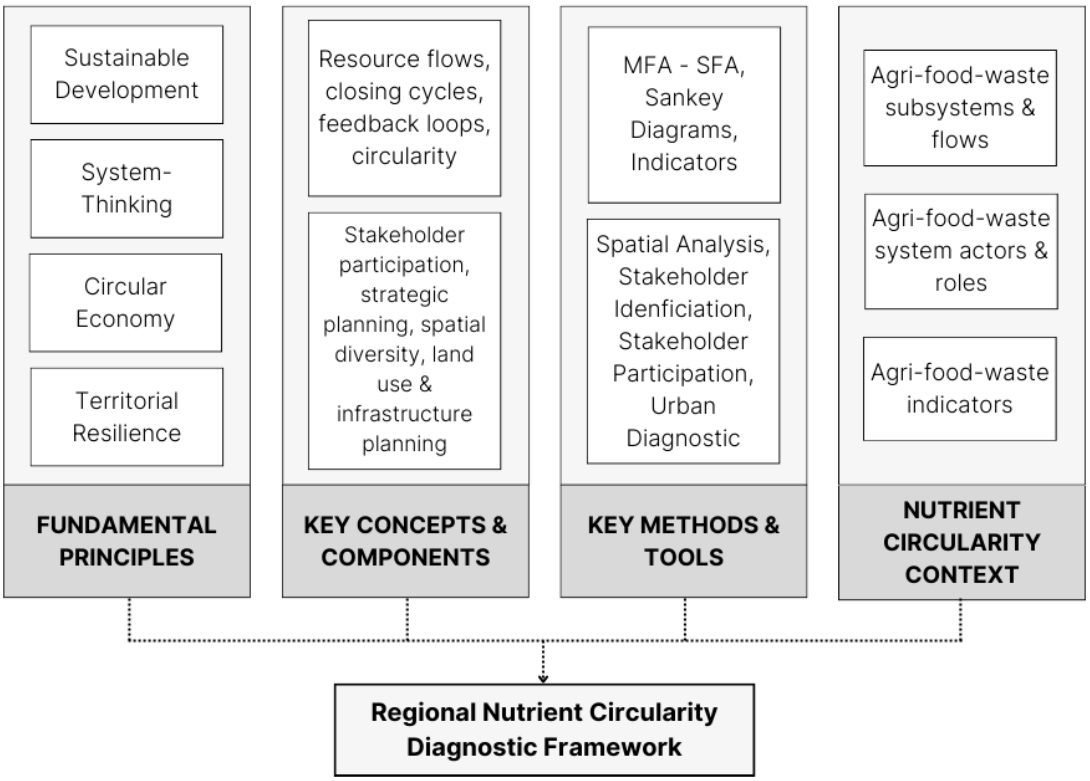


Figure 2. Summary of the theoretical framework for the Regional Nutrient Circularity Diagnosis Framework, from Fleitas Girett et al. (2024).

4.2.3. Scenario Development

Continuing with the UN planning framework, after completing the “Assessment” phase with ***Analysis & Diagnostic*** (Phase I, Block D, Step 16), the following “Planning” phase begins with ***Scenario Building*** (Phase II, Block E, Step 17). Before discussing this step further, it’s important to outline the following steps of Phase II, which include *Strategic Visioning Workshop, Formulation of Strategies and Initiatives, Environmental and Social Impact Strategy for the City,* among others, culminating in a **Strategic Development and Spatial Plan**. This final document serves as a roadmap towards a collectively envisioned future, outlining future actions and next steps.

This context is crucial when considering scenarios. The objective of building scenarios is to explore possible futures, allowing stakeholders and planners to assess different benefits, risks, and trade-offs, as well as the strategies they require. Scenarios need a future end-goal and a pathway towards that goal. They can be prescriptive, exploratory, or normative. A wide variety of inputs can be used to develop scenarios, ranging from direct interpretation from literature or stakeholder interviews to complex analyses using Bayesian networks, fuzzy logic, feedback loops, agent-based modeling, among others. Scenarios can employ either forecasting or

backcasting perspectives and can be developed using qualitative and/or quantitative methods, depending on the objectives and intended applications (Ariza-Álvarez et al. 2021).

In scientific research, there is a predominance of quantitative assessment-based scenarios, which often rely on estimations and assumptions expressed through equations and inputs. However, while numerical outputs can give a sense of precision, they can be difficult for stakeholders to interpret and can give a false sense of accuracy. Meanwhile, qualitative scenarios can integrate and communicate information from diverse perspectives and disciplines, especially useful for planning exercises and policy formulation, yet can be considered 'unscientific' due to their unstructured or unclear development. Given these considerations, many authors advocate for the combination of qualitative and quantitative scenarios as the most effective approach to explore possible futures(references). When focusing on sustainable urban development and integrated scenarios, the IPCC's (Intergovernmental Panel on Climate Change) "Shared Socioeconomic Pathways" (SSP) and "Representative Concentration Pathways" (RCP), which replace the previous Special Report on Emission Scenarios (SRES), are considered essential references for assessing environmental policies, especially in the context of the SDGs (Szetey et al. 2021; Lehtonen et al. 2021). These global scenarios combine qualitative elements, through narratives or storylines, with quantitative elements using integrated assessment models (IAMs). This method aligns with the widely-used "Story and Simulation" (SAS) approach for scenario development, which describes futures through both textual and numerical information, effectively engaging a variety of stakeholders and experts (Alcamo 2008).

As can be seen in **Figure 3**, after establishing a 'scenario guidance team and panel' composed of experts and planners (Step 1.1), information is collected from local stakeholders, adhering to an essential principle of urban planning (Step 1.2). Next, objectives and focus areas are determined by incorporating stakeholder inputs and information from key policy and planning documents (Step 1.3). Following this to Step 1.4, focal questions are developed by exploring triggering issues, leading to the creation of "what if" questions (Durance and Godet 2010). These questions or issues are usually validated and reassessed with stakeholders before proceeding to the construction of storylines. Finally, zero-order draft storylines are constructed (Step 2.1). In the next section, we examine these concepts and the elements that compose them. Identifying the key components of narratives allows for a more systematic and transparent structure, which is crucial for producing reliable and reproducible outcomes.

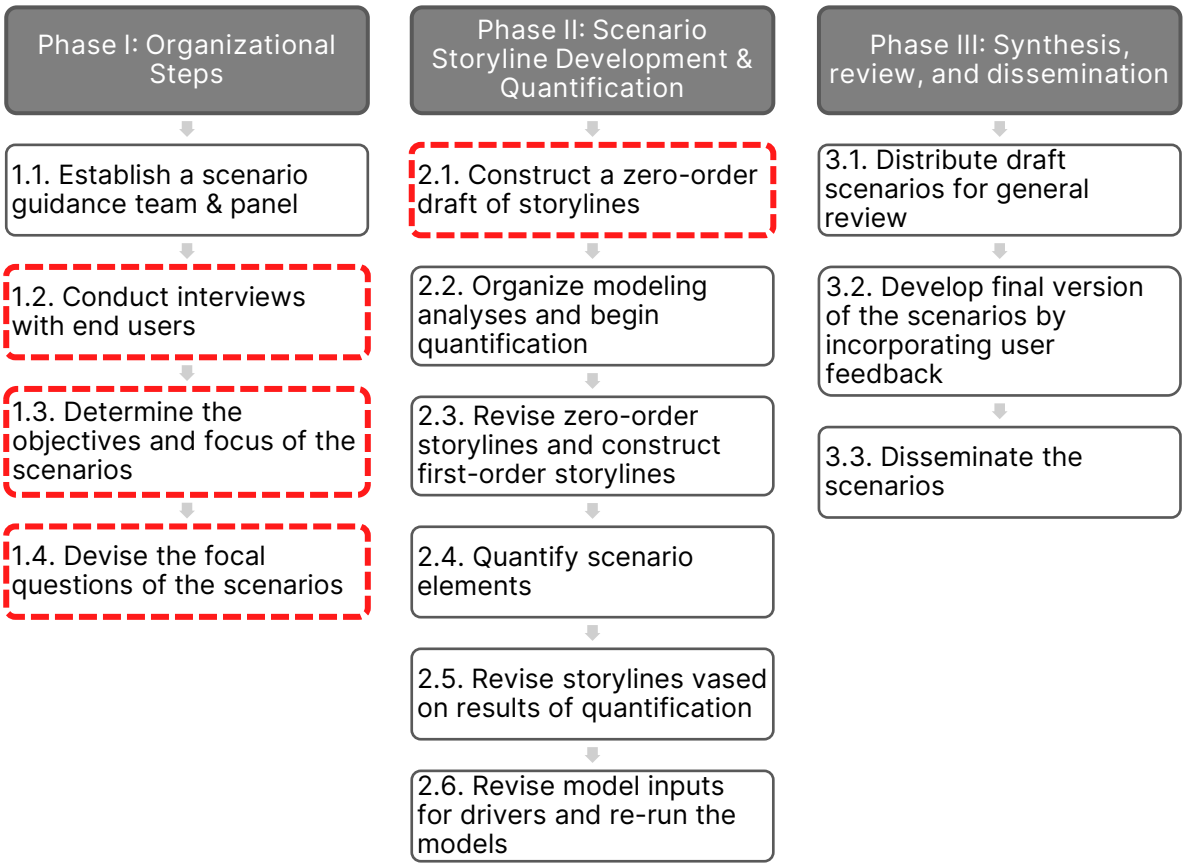


Figure 3. Methodology for Scenario Development, based on Alcamo et al. 2005.

Boxes outlined in red are those applied in this paper.

The use of narratives or stories to frame transitions and address complex, "wicked" problems is extensively explored, mostly in the social sciences (van Hulst 2012; Veland et al. 2018; Ameel 2022). This approach can be linked to 'a basic and natural human process whereby humans, individually and collectively, seek to make meaning of their experiences, perceptions, problems, and presumably, the actions they take to address problems' (Blignaut and Aronson 2020; Buchenau et al. 2023; Luederitz et al. 2017). In urban planning, narratives serve as a form of storytelling that facilitates communication and connectivity among actors around a transition. These narratives describe how events, forces, and changes unfold in the future, connecting various stakeholders, from technical experts to political decision-makers (Mallampalli et al. 2016).

In literature studies, a "storyline" is synonymous with "narrative" and generally refers to a series of events that occur within a specific time and place. It usually includes a protagonist or main characters, an overarching goal, and a plot involving the events to overcome a main challenge or conflict (through transformation and/or problem-solving strategies). Narratives typically convey an underlying lesson connected to the story's outcomes. While terminology

may vary, there is general agreement that a narrative or storyline includes the following elements (Marchau et al. 2019):

- Purpose – the goal or need that drives the characters and plot
- Context – a setting in which the characters and events occur
- Characters – the actors part of the “system of interest”
- Variables – the elements that change or evolve throughout the plot
- Outcomes – the results of the changes and events, both positive and negative, expected and unexpected

According to findings by Bijon et al. (2023), industrial symbiosis narratives designed to support future planning processes do not necessarily require technical detail; rather, it is more important that they are based on an understanding of existing sociotechnical conditions and underlying contexts. This means developing context-specific narratives that address local goals, challenges, and opportunities, extending beyond objective, empirical information. This contextualization is an essential precursor to building scenarios (Marjanović et al. 2022); however, narratives are not constrained by local contexts or immediate concerns of planners and decision-makers. Instead, they should enable exploration of possibilities, presenting varying degrees of change.

4.2.4. Nutrient Circularity

The concept of nutrient circularity (NC) has been explored by multiple authors, including (Rosemarin et al. 2020; van der Wiel et al. 2021; Teleshkan et al. 2024; Wielemaker 2019). Research on nutrient circularity typically focuses on the agri-food system, including its “waste” component, and examines organic material flows containing macronutrients such as nitrogen, phosphorus, and potassium. There is growing interest in expanding the scope of analysis to encompass a wider variety of activities and materials, extending beyond rural areas to include urban environments. This approach enhances the potential to close nutrient cycles effectively.

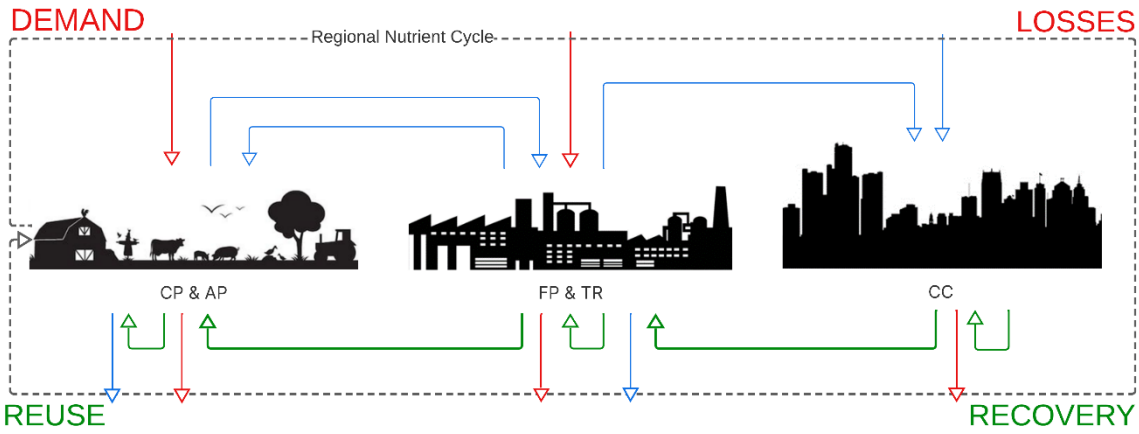


Figure 4. Main principles of regional nutrient circularity. Red = detrimental flows (to reduce), Blue = wellbeing flows; Green = opportunity flows (to increase). Based on Fleitas Girett et al. 2024. For symbol definition see Table 1.

In our previous work, we conducted a comprehensive review across various disciplines to identify factors influencing the management of nutrient-containing flows in metropolitan areas (Fleitas Girett et al. 2023). This review identified 12 factors categorized under four central themes: material flow potential, value chain characteristics, knowledge base, and institutional support (more information in **Appendix A**). In terms of grouping the activities and actors that make up the agri-food-waste system, van der Wiel et al. (2021) suggests that nutrient circularity strategies should consider the following five subsystems: crop production (CP), animal production (AP), food and feed processing industries (FF), commerce and consumption (CC), and waste treatment and recycling industries (TR). Building on insights from other authors on circular resource management, we outline four primary objectives of nutrient circularity:

1) reducing the demand for raw materials,
2) minimizing nutrient losses to the environment,
3) enhancing nutrient recovery from waste streams, and
4) promoting the reuse of recovered nutrients in productive activities.

Furthermore, in Chapter 3, we proposed a flow classification system linked to these objectives: detrimental flows (linked to objectives 1 and 2) that should be reduced, opportunity flows (linked to objectives 3 and 4) that should be increased, and 'wellbeing' flows (mainly food and feed contained nutrients) representing intentional flows deemed crucial for the local population's wellbeing (**Figure 4**).

Strategies aiming at achieving resource circularity in cities and regions require a systemic approach that goes beyond typical waste-oriented strategies to include efforts to reduce the demand of raw materials and minimize losses at multiple stages of production and

consumption. Narratives can play a crucial role to achieve this aim by proposing interventions in policy objectives and strategies (Luederitz et al. 2017), connecting policies and actors as well as addressing possible drivers, uncertainties, trade-offs, interdependencies, and conflicts (Rounsevell and Metzger 2010). In the following section, these concepts are integrated into a methodological framework useful to develop such narratives, which was subsequently applied and tested in the Metropolitan Region of Santiago.

4.3. Methodological Framework

The framework proposed in this study aims to connect the *analysis and diagnostic* step with the *scenario building* step through ***narratives***, bridging the “Our City Plans” framework proposed by UN Habitat (2022) and the SAS approach proposed by Alcamo (2008). The development of scenario narratives is comprised of three main tasks: (i) data contextualization, (ii) synthesizing findings, and (iii)constructing the narratives themselves. The first and second task focus on gathering and categorizing information related to nutrient-containing flow management from three sources: the strategic multi-dimensional diagnosis, the main relevant national and regional policy documents, and stakeholder inputs. This task involves the development of focal questions, collection of stakeholder feedback, and lastly, the identification and connection of narrative elements. These steps are detailed in the following sections and summarized in **Figure 5**.

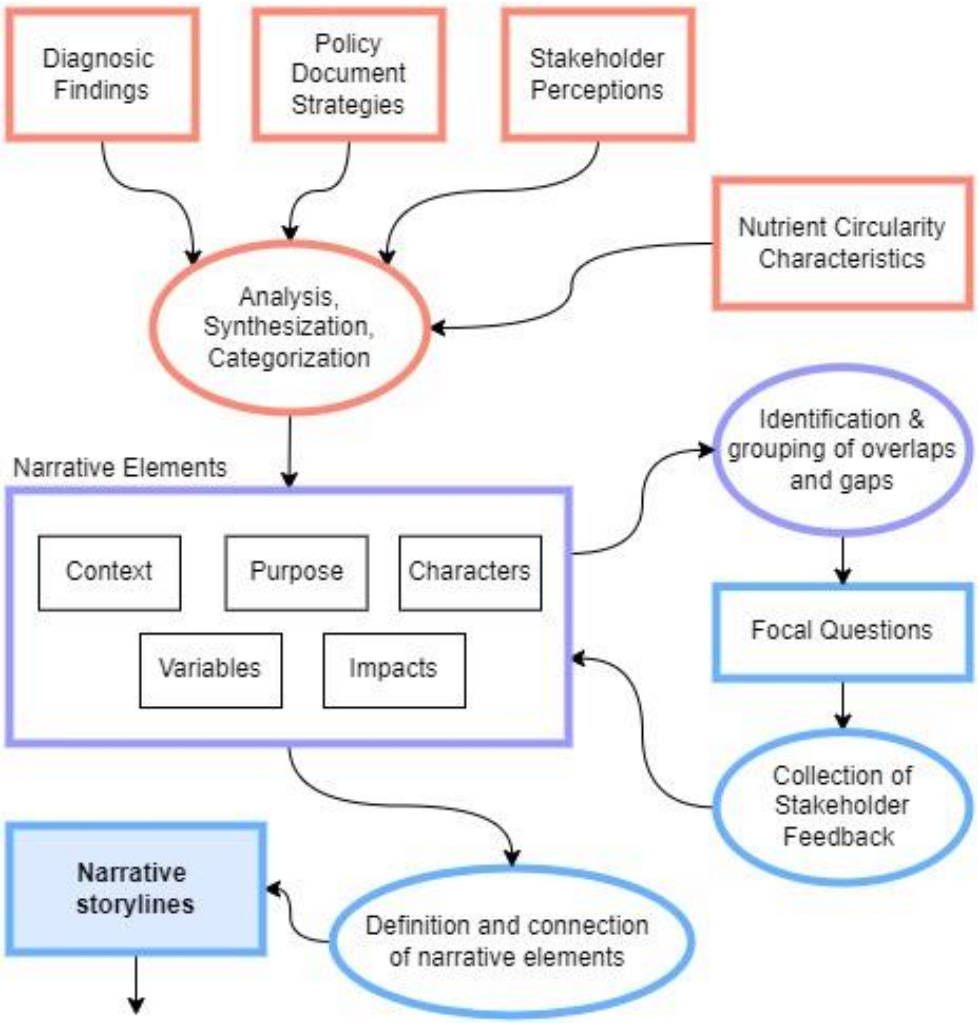


***Figure 5**. Overview of methodological framework for the construction of narratives. The red outline represents steps in the **assessment** phase, the blue outline represents the **planning** phase steps. The step outlined in purple represents the step that links both phases into the construction of narrative elements.*

4.3.1. Gathering context information

The above mentioned three sources of information, i.e. diagnosis, stakeholder input and policy documents are reviewed to identify main challenges, opportunities, strategies and priorities across all NC subsystems in the context of nutrient circularity objectives. While the diagnosis and stakeholder inputs are best suited for identifying challenges and opportunities, policy documents are primarily used to identify priorities and strategies.

The three-dimensional diagnosis has been carried out and reported in previous research. The second step involving the identification of main policy documents is done by means of reviewing institutional websites and reports to find national and/or regional plans addressing key NC issues and objectives. These plans should encompass the variety of activities and materials that existing in the system, such as urban waste management, sustainable agriculture, circular resource management in industries, among others. Once identified, these

documents are processed and characterized considering three categories, i.e. the institutions involved in their elaboration, the overall and specific objectives of the plan, year published, and the proposed actions or priorities they outline. These actions and priorities are then further organized according to NC objectives and targeted subsystems.

To collect stakeholder perceptions, actors are identified using key policy documents, followed by the application of the snowball method during interviews to identify additional relevant actors. Stakeholders from various roles, subsystems, and activities related to the management of nutrient-containing flows are to be included in this step, based on the actor characterization made during the diagnosis (Fleitas et al. 2024). Next, stakeholder insights are also collected and processed. Inputs can be gathered through structured interviews and/or workshops during and/or after the diagnosis phase.

Case Study: For the review of key policy documents related to the subsystems and objectives of nutrient circularity, we considered both national and regional plans, limiting our selection to those published within the last five years to ensure relevance to current issues and priorities. In this case study, both interviews and workshops were employed to gather information. Questions were tailored to address organizational goals, barriers, priorities, and strategies. Semi-structured interviews were conducted both virtually and in person, and then transcribed for analysis. Additionally, a workshop using the "World Café" methodology was conducted. In this workshop, 3 tables were set up with specific topics related to nutrient circularity in the region: 1) shared goals, 2) main barriers, and 3) initial steps. Stakeholders participated in multiple 15-minute rounds, rotating between tables to provide their perspectives on each topic and build upon the inputs from previous rounds. Insights were recorded on worksheets at each table and later digitized.

4.3.2. Synthesizing information

The development of the intended qualitative narratives aims to be rigorous, transparent, and replicable; for this, the synthesization of information is based on the Gioia Methodology's key principles and steps (Gioia et al. 2013). This involves rich, participative data collection, the identification of 'first-order concepts' and second-order themes, and finally, the grouping of these into aggregate dimensions that form the basis of theoretical contributions. For this research, first-order concepts are variables, second-order themes are the nutrient circularity characteristics (subsystems, objectives, and IF central themes), and the aggregated dimensions are the focal questions.

First, the findings from all three sources—diagnostic assessments, policy documents, and stakeholder inputs—were integrated by identifying common variables. These variables capture all aspects of the current situation related to identified challenges, opportunities, strategies, and priorities. Second, they were then organized according to their source and categorized by nutrient circularity characteristics, including subsystems, influencing factors, and objectives (

Table 1).

Table 1. Classification of variables according to source and nutrient circularity characteristics.

Variable Source	Diagnostic	
	Policy Document	
	Stakeholder Input	
	FQ Feedback	
Nutrient Circularity Characteristic		**Symbol**
Subsystem	Crop Production	CP
	Animal Production	AP
	Food & Feed Processing	FF
	Commerce & Consumption	CC
	Treatment & Recycling	TR
Objective	Reduce Demand	RD
	Reduce Loss	RL
	Increase Recovery	IC
	Increase Reuse	IU
	Systemic	SY
IF Central Theme	Material Potential	MP
	Value-Chain Characteristics	VC
	Knowledge Base	KB
	Institutional Support	IS

This integration and contextualization of information allows for the development of narratives having three main characteristics: (i) address the material, spatial and social challenges and opportunities identified in the multidimensional diagnosis, (ii) align with local objectives and strategies outlined in key policy documents, and, (iii) take into account stakeholder concerns and interests expressed in interactions.

4.3.3. Constructing the narratives

For the final step of aggregating dimensions, focal questions are developed. Following the SAS approach, these "what if" questions form the foundation of narratives and entail identifying overlaps and gaps between the variables identified in previous steps. In the following step, these overlaps and gaps are connected through common subsystems and/or

NC objectives. Focal questions propose modifications to the variables that compose these challenges and opportunities. To ensure a systemic perspective on nutrient circularity, it is essential to address all subsystems and NC objectives, even if they are distributed across different proposals. This underscores the complementary role of narratives in exploring potential futures.

In the second step, these questions are presented to strategic stakeholders, and feedback is collected. Stakeholders included in this step should represent a variety of subsystems and sectors, focusing on those identified as having ‘articulating’ or ‘planning’ roles in the diagnosis. Moreover, stakeholders should be aware of and have access to the main diagnostic findings. Various tools can be used to collect feedback, such as surveys, interviews, and workshops. In a next step, after being presented with the focal questions, stakeholders should be asked to provide their feedback on potential weaknesses and strengths of each proposal, as well as possible connections with actors and/or policies, which should be recorded for further analysis. This validation step allows for the reinforcement and introduction of variables to those identified in previous steps. Moreover, they provide insights regarding perceived implications of modifying these variables.

Finally, scenario narratives are constructed using findings from previous steps to define their constituting elements: Purpose, Context, Actors, Variables, and Outcomes. The detailed description serves to connect all the elements into a **storyline**, proposing future actions and strategies that affect the identified variables, and explores the potential implications of each narrative, including benefits, risks, dependencies, and trade-offs.

Case Study: In this case study, focal questions were presented at a workshop that brought together strategic stakeholders with "articulating" and "planning" roles related to the agri-food-waste system from various sectors, based on the stakeholder typology presented in the MRSC Diagnostic. Participants were organized into roundtables, each of which was assigned a worksheet presenting one focal question. Discussions at each table were guided by facilitators, who recorded feedback onto the worksheets. These worksheets were later digitized for further processing.

4.4. Case study results

4.4.1. Synthesizing & contextualizing for the MRSC

The key documents identified for the document review are listed in Table 2, and their analysis is summarized in Appendix B. From this review, two overarching goals were identified in relation to nutrient-containing flows: A Shared Goal 1: Increasing the recycling of municipal

organic waste, and a Shared Goal 2: Promotion of sustainable agricultural production. Along with other materials.

Shared Goal 1 is focused on reducing the disposition of solid waste in landfills, driven by high economic costs, environmental emissions, and logistical complexities. Meanwhile, Shared Goal 2 focuses on increasing the resilience of local agriculture and supporting the economic growth of the sector while considering social and environmental sustainability. This responds to the threats of climate change, external resource dependency and increasing urbanization, in the context of an increasingly globalized market.

Table 2. Key policy documents reviewed for this case study.

Document	**Year**
Estrategia Nacional de Residuos Orgánicos (ENRO) – Chile 2040	2022
Hoja de Ruta para un Chile Circular al 2040	2021
Plan de Acción de Hoja de Ruta EC - Región Metropolitana	2024
Política Nacional de Parques Urbanos	2021
Estrategia Nacional de Soberanía para la Seguridad Alimentaria	2023
Estrategia de Sustentabilidad Agroalimentaria 2020-2030	2021
Estrategia INDAP 2023-2030	2023

Next, stakeholder insights regarding goals, barriers, strategies, and priorities were collected and organized. First, transcriptions were reviewed from 30 interviews carried out with actors from public and private sectors, as well as academia and NGOs. Among the stakeholders interviewed, all but the “Food & Feed Industries” subsystem was contacted, despite numerous attempts to establish contact. Next, the “World Café” workshop digitalized outputs were also reviewed and organized. Of the stakeholders present for the workshop, all represented public and private sector organizations linked to either the “commerce and consumption” or “treatment and recycling industries” subsystems. This resulted in perspectives mostly focused on Shared Goal 1. Findings from these engagements are detailed in Appendix C & D.

Regarding material flow potential, the main challenges noted were insufficient waste treatment and recycling infrastructure and technology, which were linked to feasibility constraints regarding transportation distances, land costs, and mixed waste streams, as well as regulatory limitations regarding facility installations and secondary material applications. In terms of value chain characteristics, a wide variety of challenges were noted: lack of awareness regarding waste management and recycling, lack of trust in secondary materials, resistance to change

behaviors and practices, financial and technical constraints to innovate or change practices, lack of consideration of social and environmental costs, lack of collaborations between sectors, as well as limited connection between private sector and public or academic institutions.

In terms of the local knowledge base, challenges include the lack of independent research and publicly available information regarding secondary materials and businesses, as well as lack of training (and thereby professional) regarding circular practices and recovered materials, along with important influence from mineral fertilizer companies through technical advice. Finally, the main challenges regarding institutional support concerned outdated regulations (as mentioned above regarding material flow potential), as well as insufficient protocols and capacity for the management of urban waste and green area, linked to insufficient and unequal distribution of resources among municipalities, as well as limited articulation within and between government institutions at national and regional levels.

Finally, variables were identified from policy documents and stakeholder inputs (interviews and workshops), as well as the strategic multidimensional diagnosis, and organized according to subsystem, influencing factor, and NC objective. Over 180 variables were identified and classified according to the system proposed in Table 1. This analysis is summarized in **Table 3**.

Table 3. Variables identified in the diagnosis, policy documents, and stakeholder inputs, for all subsystems (i.e.xxx).

Central Theme	Reduce Demand	Reduce Losses	Increase Recovery	Increase Reuse
Material Flow Potential	Mineral fertilizer use	Emissions from CP and AP; Food market waste; degraded soils; municipal recycling; organic solid waste; WWTP emissions; Overfertilization; FF byproducts; TR technologies;	Waste treatment and recycling infrastructure; Quality of recovered material flows; transportation costs; land availability and costs;	Distance between AP and CP activities; Distance between TR and CP activities; garden and green area fertilization; sustainable soil management; CP surface area & diversity; quality of secondary materials;
Value Chain Characteristics	Influence of mineral fertilizer businesses; Mineral fertilizer prices & availability; Fertilization practices;	Circular business design; Food sharing platforms; Cleaner Production agreements;	Education regarding waste separation; interest in revalorization and circularity;	Trust & interest in secondary materials; Secondary material prices and availability; trust among actors; Circularity in educational curriculum
Knowledge Base	Training regarding use of bio-inputs / secondary materials;	Circular / eco product designs; Training in circular production;		Database of recovered materials and/or businesses; Pilot projects; R&D for agro-industries; Independent research with shared data;
Institutional Support		Soil quality regulations; Consideration of environmental costs; material traceability legislation;	Municipal waste management fees & budget; Regulations regarding environmental impact assessments for TR; Regulations regarding zoning;	Regulations regarding application of recovered materials; circularity addressed in policy documents; product standards and certifications; subsidies and incentives;

4.4.2. Construction of narratives

Using the information from the previous steps, overlaps and gaps of the main challenges, opportunities and strategies were identified. These 'topics' were then linked to variables that were shared within subsystems and/or NC objectives (refer to **Section 2.2**), with the goal of creating strategic proposals that could potentially link common sectors and/or interests.

- FQ 1: **What if composting capacity is increased and green urban areas are maintained with nutrients recovered from municipal waste?**

This question was developed to target Shared Goal 1, focusing on the urban context. Considering the existing policies and strategies that are already in place or being actively developed towards Shared Goal 1, this proposal aims to provide more insight into options and considerations applicable in the short-term (~1-2 years). In terms of the four main concerns of nutrient circularity, this alternative focuses on decreasing losses as well as increasing recovery and reuse. Diagnostic findings confirm that significant nutrient losses occur due to the disposal of organic solid waste in cities. Specifically, 82% of nitrogen (N), 57% of phosphorus (P), and 95% of potassium (K) destined for landfills come from household food and garden waste, making these flows a priority. Composting plants are located on the periphery of urban areas, while urban parks are distributed around the region and near city limits, presenting a valuable opportunity to close nutrient cycles within short geographic distances.

- FQ 2: **What if animal residue nutrients are used more efficiently and applied to more types of crops?**

This question focuses on Shared Goal 2, emphasizing targeting rural and peri-urban areas. There are already planning processes that are considering this issue, but because regulations are still quite limited, it can be expected that this sort of change would require a more mid-term planning process (~5 years). Out of the four priorities of nutrient circularity, this alternative focuses on reducing demand and losses of nutrients. Diagnosis findings confirm that the most significant source of nutrient losses from productive activities is due to volatilization and leaching from croplands. This primarily occurs from the application of minimally processed chicken and swine manure on soils already saturated with nutrients from the overfertilization of industrial crops like maize using mineral fertilizers (Fleitas-Giret et al., 2024). This nutrient over-saturation is often spatially concentrated, and stakeholders have expressed significant interest and financial capacity, specifically from large farmers and agri-businesses, to address these challenges. This validates the selection of this topic as both a main priority and a strong opportunity to enhance nutrient circularity in the region.

- FQ 3: **What if WWTP could incorporate new technologies and sludge nutrients could be applied to crops such as fruits and vegetables?'**

This question addresses an issue that is most evident in the strategic diagnosis, integrating both urban and rural areas,which is currently minimally addressed by existing planning processes and stakeholders. Moreover, it holds important regulatory constraints and technological considerations that require more long-term planning (~10 years). The diagnosis findings identify wastewater treatment as the top recovery occurring in the MRSC, as well as the main source of nutrient losses. This is due to current treatment processes that leave a great portion of the nutrients in the treated wastewater thereby being released into the environment either through volatilization or in the treated effluent deposited to water bodies, with a portion remaining in sludge that is either applied to industrial croplands or deposited in a monofil from where it is also brought gradually back into crop production activities mostly outside the Metropolitan region. Moreover, the main organization in charge of wastewater treatment in the MRSC is highly interested in this issue and has financial and technical capacity to develop and implement changes.

These focal questions were presented to stakeholders as a workshop held in Santiago, Chile on December 6th, 2024. Their feedback was collected, processed, and summarized in Table 4.

Table 4. Summary of feedback received for each focal question (FQ).

FQ	Feedback
1	• Existing environmental regulations and procedures needs to be adapted to composting plants, resulting in quicker and simpler evaluation and licensing for projects • Regional government should lead this initiative, since it goes beyond municipal limits • Since electoral periods are short and projects can be long, it may be best to work with municipal and sectoral associations • Associative/community solutions should be prioritized, because depending on at-home composting is unfeasible • Educating the population is key to establish shared responsibility and ensure adequate separation as the best solution • Ideally, compost produced by each commune should be used for its own parks
2	• It's important to work with producers to increase awareness and trust of organic fertilizers • Biosecurity is vital and current treatment of these materials cannot ensure this • The availability and quality of these materials needs to be improved
3	• Existing regulations must be updated to consider different scales and applications • Recovery, treatment and application of materials should be responsibility of sanitary organizations, without generating more costs for farmers • Recovered materials should be available through different mediums, like granular or pelletized products

4.4.3. Narratives

The narratives for the Metropolitan Region of Santiago are presented below. As described in the methodological section, these narratives are considered "zero-order" drafts, serving as preliminary outlines to condense diagnostic and contextualization analyses and identify key elements for future scenario exploration. These elements are summarized in the following tables, and explained in more detail in Appendices E-G.

Table 5. Narrative 1 - Closing Urban Nutrient Loops.

Narrative Elements	
Purpose	Restore and enhance the public green areas of Santiago with compost from household waste.
Context	Short-term; TR – CC subsystems
Key Actors	Ministerio de Vivienda & Urbanismo & SEREMI; Ministerio de Ambiente & SEREMI; GORE; Ministerio de Salud & SEREMI; Ministerio de Agricultura & SEREMI; Municipalities; landscaping providers; composting industries; neighborhood associations;
Variables	Fertilization practices; training regarding use of bio-inputs / secondary materials; organic solid waste management; TR technology; TR infrastructure; water conservation; transportation costs; land availability & costs; education regarding waste separation; interest in circularity; municipal waste management fees & budgets; environmental impact assessment regulations; zoning regulations; quality of secondary-materials; prices & availability of secondary materials; product standards & certifications; subsidies & tax incentives; collaboration between organizations;
Main storyline points	1. Co-design action plan, with designation of responsible actors, and mobilization of resources 2. Implement separate waste collection systems for organic and inorganic residues 3. Assess appropriate locations for TR activities (prioritizing composting technologies) 4. Offer financial incentives for TR activity development 5. Update regulatory framework regarding TR activities 6. Develop protocols and criteria for public green area management 7. Standardize and certify compost 8. Capacity building for citizens, municipalities, and landscaping providers 9. Support research & development for technological and business innovations

Implications	**Benefits**: close urban nutrient cycles; reduce losses to landfills; improve vegetative landscaping in public green areas; strengthen secondary organic material market (compost, fertilizers, etc.) **Risks**: dependence on political will; need for integration with existing development plans and protocols; community reactions regarding TR projects; long adjustment period for waste separation quality & value chain dynamics **Trade-off**: decentralized on-site waste treatment (currently promoted) vs more centralized interventions (larger loops) **Uncertainties**: complex relationships between landfill companies and municipalities

Table 6. Narrative 2 - Closing Nutrient Loops in Agriculture.

Narrative Elements	
Purpose	Increase effective nutrient reuse and revalorization between animal and crop farms, reducing dependence on imported fertilizers.
Context	Medium-term; AP – CP subsystems
Actors	Ministry of Agriculture & SEREMI; INDAP; SAG; ODEPA; INIA; FIA; CIREN; FUCOA; Municipalities; Universities; Agricultural Sector Organizations; Rendering industries
Variables	Mineral fertilizer use; fertilization practices; Training regarding use of bio-inputs / secondary materials; CP and AP emissions; contaminated soils; waste treatment technology; Cleaner Production agreements; soil quality regulations; transportation costs; interest in circularity; secondary-material regulations; CP surface area & diversity; quality of secondary-materials; trust & interest in secondary materials; prices & availability of secondary materials; trust among actors; R&D for agro-industries; product standards & certifications; subsidies & tax incentives; collaboration between organizations;
Main storyline points	1. Establish interinstitutional and multi-sectoral working group to promote circularity in agriculture 2. Integrate circular agriculture practices and products in university curricula & agricultural training programs for farmers, extensionists, agroindustry merchants, etc. 3. Expand soil quality legislation to encourage nutrient use efficiency 4. Increase publicly funded research regarding areas of nutrient saturation/depletion, development & use of secondary materials/products 5. Develop & disseminate best practices for sectors, with variety of scales and interventions

	6. Provide financial incentives and subsidies to farms and organizations for the adoption of circular practices & technologies 7. Support existing and new biorefineries, providing R&D funding for standardization and scaling of operations, business model research, and development of specialized products 8. Incentivize TR industries and projects receiving public funds to share non-confidential information (courses, seminars, etc.) 9. Develop regulatory framework and public database for certified / approved secondary products
Implications	**Benefits**: reduced dependence/demand on imported fertilizers; strengthened resilience of agri-food systems; improved waste management, especially regarding waterbody contamination; support & expansion of local biorefinery sector; increased collaboration & trust across sectors **Risks**: dependence on political will; influence of international agri-food markets and fertilizer industries; farmer acceptance and capacity; acceptance of quality and price of secondary products by producers; **Trade-off**: increased pressure for animal waste management could impact small farm viability **Uncertainties**: zoning considerations regarding biorefinery installation and expansion; future of agricultural activities in MRSC;

Table 7. Narrative 3: Connecting Urban and Rural Nutrient Cycles.

Narrative Elements	
Purpose	Increase food security by fertilizing fruit and vegetable crops with nutrients recovered from WWTP.
Context	Long-term; CP – TR subsystems
Actors	Ministry of Agriculture (MinAgri) & SEREMI; SAG, INIA, INDAP, ODEPA; Ministry of Environment (MMA) & SEREMI; Ministry of Health (MinSAL) & SEREMI; Regional Government (GORE); Rural municipalities; Crop farms (fruits, vegetables); Biotech/Biorefinery startups; WWTPs; Agricultural sector associations; agro-industry merchants; food production/sector associations;
Variables	Mineral fertilizer use; fertilization practices; Training regarding use of bio-inputs / secondary materials; transportation distances and costs; interest in circularity; secondary-material regulations; CP surface area & diversity; quality of secondary-materials; trust & interest in secondary materials; prices & availability of secondary

	materials; trust among actors; R&D for agro-industries; product standards & certifications; subsidies & tax incentives; collaboration between organizations;
Main storyline points:	1. Expand soil quality legislation to encourage nutrient use efficiency 2. Assess and incorporate nutrient recycling technologies for WWTPs to increase recovery of nutrients from wastewater & transform recovered nutrients (from wastewater and sludge) into high-quality secondary products 3. Support collaborations between WWTPs and biorefineries 4. Allocate resources for R&D related to WWTP secondary products 5. Review and update regulations regarding the use of secondary products, expanding to their use for food crop production (fruits and vegetables) 6. Offer incentives for TR industries and projects to share non-confidential information (articles, courses, seminars, etc.) 7. Integrate circular agriculture practices and products in university curricula & agricultural training programs for farmers, extensionists, agroindustry merchants, etc. 8. Establish comprehensive communication plans with the food industry sector and with the general public, sharing benefits and risk management regarding secondary products
Implications	**Benefits**: increased recovery of nutrients; closing / reducing of critical nutrient loop in the region; collaboration between urban and rural actors; reduced dependence/demand on imported fertilizers; strengthened resilience of agri-food systems; improved waste management, especially regarding waterbody contamination **Risks**: dependence on political will; influence of international agri-food markets and fertilizer industries; acceptance and trust from actors across the entire agri-food-waste system; lack of experience and trust in nutrient recycling technologies **Trade-off**: biogas production for some nutrient flows may be necessary for feasibility of technological innovations **Uncertainties**: international cooperations to guide the development and implementation of innovative nutrient recycling strategies; food market trends regarding the use of secondary products;

4.5. Discussion

4.5.1. Synthesization and Contextualization

This step was crucial for several reasons, significantly adding value to the narrative development process. First, the diversity of information sources enriched and expanded the construction of narratives with different types of variables. The multidimensional diagnostic

provided evidence-based material and organizational insights regarding key nutrient circularity opportunities and challenges. Policy documents offered a foundation of existing strategies and goals, while stakeholder engagements revealed perceived and potential implications of interventions not always evident in documents and scientific analyses. Consequently, the narratives were developed not only from technical and quantitative analyses but also from the interests of value chain actors, policymakers, and planners, enhancing their feasibility and acceptance. This comprehensive foundation ensures that the narratives are well-rounded, realistic, and aligned with the interests and concerns of all relevant parties.

Identifying overlaps and gaps within these diverse sources was crucial for constructing effective narratives. The overlaps of variables across subsystems and objectives allowed for the definition of narrative purposes that resonate with those involved in planning processes, thereby presumably enhancing their relevance and impact. This also enabled the identification of relevant actors linked to these variables, considering their responsibilities, roles, concerns, and interests. Additionally, by connecting narrative elements that align strongly with existing goals and strategies, the narratives may be perceived as more feasible and applicable, and they are more likely to be implemented quickly compared to those with more gaps, giving an important indication of narrative context. Beyond overlaps, this step is also essential to identify and bridge gaps between different subsystems/sectors and objectives. For example, challenges identified in the diagnosis that are not addressed in policy documents and strategies are highlighted through our categorization system, which considers all subsystems, factors, and objectives related to nutrient circularity. This approach ensures that the narratives are systemic.

In summary, this step is vital for two main reasons: a) identifying narrative elements that strongly overlap between sources, allowing for the construction of narratives that link goals, actors, and strategies that may currently be fragmented; and b) identifying narrative elements that are disconnected between different sources, which can be used to enrich more popular narratives or build alternative ones. These alternative narratives can highlight previously overlooked variables, encouraging the exploration of options not considered in existing plans. This point is also highlighted by (Marjanović et al. 2022), who suggests that planners and policymakers should place greater emphasis on local knowledge and insights related to activities and practices carried on in their context.

4.5.2. Construction of Narratives

This approach to narrative construction aligns with existing approaches, such as development of shared socioeconomic pathways (O'Neill et al. 2017; Riahi et al. 2017). In addition, this approach offers a framework in which all relevant information is systematically organized,

leading to a more transparent, systematic and systemic narrative development process. This allows for traceability and consistency, which is essential for a robust transition from data analysis to storytelling (Carbonell et al. 2017). By focusing on the overlaps between variables, subsystems, and objectives, it becomes evident which storyline elements can be strategically linked to propose key actions. This is vital to clarify and validate the direction of each narrative. Moreover, this approach not only highlights which variables and actors are essential for a narrative, but also uses the categorization system to identify any relevant *missing* actions, through its systemic approach to narrative construction. By identifying and structuring narrative elements according to the framework, we ensured the creation of comprehensive yet flexible stories which can provide a strong foundation for more detailed scenario modeling and assessment in subsequent steps. Finally, by presenting three different but connected narratives in brief pragmatic descriptions, stakeholders can clearly identify the key components necessary to understand each alternative future, regardless of their background or role (Martin Gurr).

In addition, incorporating stakeholder feedback into the focal questions before identifying narrative elements was also essential. Not only does it ensure that strategic actors have a real sense of involvement, but this process also provided insights into the adequacy of synthesizing and grouping key goals and variables (Martin Gurr). Additionally, it revealed new variables that were not apparent during initial narrative development. This preliminary feedback helped refine and expand actions for each narrative, as well as for identifying any potential implications associated with each narrative. For this feedback step, it was optimal to engage strategic stakeholders who possessed the capacity for strategic thinking, were accustomed to considering diverse perspectives, and could offer valuable insights beyond technicalities.

4.5.3. Framework Limitations

The framework relies on a comprehensive diagnostic assessment, emphasizing the need for a thorough initial analysis to ensure that narratives are grounded in a strong understanding of the context. The quality of these narratives is also influenced by the policy document review, especially considering the dynamic nature of local policies. Ongoing updates and expert validation of the document list can be used to address this.

Additionally, the categorization of variables introduces some ambiguity, particularly in identifying overlaps. To address this, a dual-level system for subsystems and nutrient circularity objectives was used, using “primary” and “secondary” for each category. While this approach reduces ambiguity, some subjectivity remains in grouping variables. Also, the optimal number of focal questions is still under consideration, balancing narrative scopes with the risk of complicating the planning process.

The identification of implications is also contingent upon the comprehensiveness of prior assessments. This reliance underscores the value of considering a wide range of factors and perspectives during the diagnostic, policy review, and stakeholder engagement phases, which enriches the narrative development process. Lastly, the integration of stakeholder perspectives is crucial for robustness and systemic nature of the zero-draft storylines. The lack of integration of sufficient stakeholder perspectives can impact the robustness and systemic nature of the zero-draft storylines. Effective and consistent engagement strategies are crucial, as the reliability of stakeholder input may vary across different contexts.

4.5.4. Case Study: Metropolitan Region of Santiago de Chile

In examining the nutrient circularity (NC) objectives addressed in recent local policy and planning documents, as well as stakeholder inputs, it was observed that strategies related to Shared Goal 1 primarily focus on reducing losses and increasing recovery in urbanized areas. In contrast, Shared Goal 2 extends these efforts to include decreasing demand and increasing reuse, mostly within rural contexts. Moreover, stakeholder engagements revealed two notable insights shared by actors across sectors and landscapes: 1) the need for improved territorial planning, particularly concerning the impact of urbanization on the feasibility of productive and treatment activities, and 2) the lack of a nutrient-focused perspective, recognized as a crucial link between urban and rural contexts. The current disconnection between the two goals and their respective contexts is confirmed in all three information sources and can be attributed to spatial and material differences, resulting in a limited integration between actors and strategies in the MRSC. This gap hinders the potential for systemic solutions and underscores the necessity for a more comprehensive perspective on the circular management of nutrient-containing flows, which is currently underrepresented in existing policies and strategies.

In this case study, three focal questions were developed to explore possible futures. The first two questions aimed to address the two 'shared goals' identified in the review of policy documents and stakeholder perceptions. The third question facilitated an exploration that extended beyond current policy and stakeholder aspirations, applying a more systemic view based on the diagnostic findings. The resulting narratives effectively crossed the boundaries of subsystems, as well as the influencing factors and objectives of nutrient circularity. They also addressed elements that are still mostly disconnected or not prioritized in existing plans.

Despite our best efforts to contact actors from the Food and Feed Industry, input and perspectives from this subsystem were limited, thus resulting in insufficient representation in both the diagnostic and narrative development. However, material flow data indicated that this subsystem is already proactive with recovery and reuse of waste flows, more research is recommended in order to gather the lessons learned and challenges they foresee in fulfilling

this role. Regarding narrative construction, we believe that at this “zero-order” stage, the degree of analyses used for the diagnostic, policy document review, and stakeholder engagements is sufficient for the identification of key factors enabling change but limited for fully modeling the implications for each of them. In following planning steps, particularly the scenario development and modeling, the narrative implications are to be expanded and enriched.

4.5.5. Contribution & Future Work

The proposed framework connects the assessment phase to the planning phase by providing a rigorous model that could be adopted by other cities and planning bodies, enhancing their planning processes. While narratives are widely used in planning processes, their development often appears subjective and opaque. The narrative construction methodology proposed here provides a more systematic and transparent approach, ensuring that narratives are contextualized, feasible, relevant to stakeholders, and address actual material and social priorities.

Data collection is transparent, iterative, and participatory, and data analysis clearly specifies categorization schemes, aiming to enhance theoretical clarity (Gioia et al. 2013). Moreover, by systematically identifying and processing information from diverse data sources, the framework fosters a more transparent and participatory planning process, which is crucial for achieving sustainable and widely accepted urban development outcomes. By building narratives that are well-contextualized, the framework supports their feasibility, applicability, and acceptance among planning stakeholders. This framework also compels a systemic perspective necessary for nutrient circularity, enabling actors to consider and explore alternative strategies that go beyond current practices, based on a holistic view that supports informed decision-making and fosters stakeholder engagement (Alcamo et al. 2005; Mallampalli et al. 2016). As mentioned in (Marjanović et al. 2022), this allows for urban transitions that go beyond establishing circular economies, ‘adopting a comprehensive and context-sensitive approach instead’.

Finally, this work is also important because of its focus on a South American metropolitan area. While methods have been explored for scaling global circularity policies and frameworks to local contexts, this has almost entirely been focused on high-income or “Global North” countries. As mentioned in (Marjanović et al. 2022), many cities build their circular strategies based on cases and best practices established in regions like Europe, possibly undermining context-specific considerations and initiatives. This is an important issue considering that the Global South is where urbanization is most present and increasing, accompanied by important urban development planning processes. There is a deep and urgent need to integrate a

nutrient circularity perspective into these planning processes, and this framework can be useful to alleviate this.

Continuing the "story and simulation approach," these qualitative narratives should be subsequently quantitatively modeled and assessed (Alcamo et al. 2005). These authors underscore the value of first developing narrative storylines that allow for the consideration of a ‘broad range of elements and feedback effects that often cannot be quantified’. The subsequent iterative process allows for refinements and enhancements to the narratives’ based on quantitative data, ensuring they remain relevant and actionable (2016). Ultimately, the refined scenario narratives, combining qualitative and quantitative insights, enable a systemic exploration of future scenarios in nutrient circularity, adapted to the local context and reviewed by planning actors for comprehensive scenario development. This comprehensive approach facilitates a systemic exploration of future scenarios in circular resource management, incorporating all critical elements of nutrient circularity—such as subsystems, influencing factors, and NC objectives—adapted to the local context.

In future research it is crucial to investigate how nutrient circularity narratives can be integrated with other resource circularity narratives during scenario development to identify potential synergies and conflicts. In addition, conducting further analysis at the subsystem level could refine the framework for developing more targeted narratives for each subsystem. Furthermore, not only collecting information through stakeholder engagements but ensuring consistent sharing of findings with stakeholders is a must. This includes providing details on the methodologies used for analyses and the results, with a focus on enhancing usability for a diverse range of actors. Though beyond the scope of this study, further research is vital to understand how to optimize the presentation and communication of these narratives, such as through the use of visualizations like those proposed by (Furlan et al. 2020) or (Russo et al.). For the MRSC, beyond sharing this article, this research will be condensed into a report, translated into Spanish, and disseminated to stakeholders involved in this study, including key actors with strategic planning roles.

4.6. Conclusion

To develop an effective action plan for circular resource management in a region or city, two key phases must be followed: a) a comprehensive assessment phase culminating in a diagnostic, and b) a planning phase that begins with scenario development and concludes with a strategic vision and action plan (UN Habitat 2022). However, methods for connecting these two phases so far remain unclear, necessitating integration between urban metabolism research and urban planning practices. In this work, we designed an innovative framework to develop narratives that can bridge the assessment and planning phases of urban planning processes. This transdisciplinary framework integrates empirical information from technical

analyses with stakeholder inputs and local policies, ensuring that narratives are well-contextualized, feasible, and relevant to planning stakeholders (Marjanović et al. 2022). By systematically processing information from these sources, the framework enhances transparency and reproducibility while promoting a holistic perspective essential for circular resource management. Lastly, the resulting zero-order narratives incorporate essential story elements to facilitate the efficient development of scenarios when continuing to scenario modeling (Alcamo 2008).

By improving the connection between assessment and planning phases through narratives, a systemic perspective of nutrient circularity can be incorporated into scenario-building processes. This approach bridges scientific and political arenas by integrating urban planning narrative elements with the analytical tools prevalent in urban metabolism research. Grounding narratives in multidimensional analysis, stakeholder perceptions, and the core principles of nutrient circularity helps avoid one-sided or incomplete solutions, thereby addressing broader systemic transformations. This promotes the development of integrated and effective strategies for managing nutrient-containing flows, which are crucial for the sustainability of cities and regions. In many cases, circular city or region planning is already underway, such as the case of the MRSC. Considering the iterative nature of urban planning and policy development, these findings can be used to evaluate existing plans and strategies, as well as for adapting them in the future, illuminating alternatives that can aspire to a more systemic level of circularity in the MRSC.

4.7. Bibliography

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4.8. Appendices

A. Contextualization: Document Review Summary

Table 8. Results from policy document review

Shared Goals	Main Strategies	Planning Instruments	Main Actors	NC Priorities
1. Increase recycling of municipal solid organic waste	emphasize recovery in-situ composting of domestic food and garden waste, with reuse mainly achieved in domestic or corporate gardens and public urban parks. The installation of additional recycling plants is also included.	Estrategia Nacional de Residuos Orgánicos Chile 2040 (2022); Hoja de Ruta para un Chile Circular al 2040 (2021); Hoja de Ruta de Economía Circular 2040 - Región Metropolitana (2024)	Ministerio de Ambiente - SEREMI RM; Ministerio de Salud – SEREMI RM; Gobierno Regional RM; Municipalities; Ministerio de Vivienda y Urbanismo - SEREMI RM	reduce loss; increase recovery
2. Promote sustainable agricultural production	focus on promoting sustainable agricultural practices and products, especially regarding soil management and water conservation. They also include the promotion of research and development for agroindustries, including industrial ecology and business innovation methods for decreasing environmental impact and increasing economic competitivity.	Estrategia de Sustentabilidad Agroalimentaria 2020-2030 (2021); Estrategia INDAP 2023-2030 (2023); Estrategia Nacional de Soberanía para la Seguridad Alimentaria (2023)	Ministerio de Agricultura – INDAP, ODEPA	reduce demand; reduce loss; increase recovery; increase reuse

B. Contextualization: Workshop Results

Table 9. Responses from workshop roundtables, organized by topic and central theme of influencing factors.

	Main Barriers	Shared Goals	First Steps
Material Potential	• Deficient infrastructure for recycling • Costly transportation due to large distances • High contamination in domestic 'separated' waste	• Develop infrastructure for waste treatment and recycling	• Diagnostic of current use of fertilizers
Value Chain Characteristics	• Little interest in "garbage"; invisible problem for many • Lack of awareness regarding available recycled products • Lack of trust in bio-fertilizers • Lack of awareness regarding domestic recycling practices • Resistance to change of behaviors (linear to circular models), especially in older population • Financial constraints for smaller farmers • True costs (environmental, social) are not considered	• Foster trust among actors • Promote participation across sectors • Actors from each sector recognize their responsibilities • Raise awareness in population regarding circularity benefits • Raise demand of recovered bio-inputs for agriculture • Support the market of bio-inputs • Effective communicate with end users regarding goals, benefits, procedures, etc.	• Promote eco labels • Group actors and understand expectations • Communication strategies for citizens, schools, neighborhood committees, etc. • Use social media (ex. Whatsapp groups) to support participation and engagement • Offer practical solutions and support to increase participation (courses, etc.) •
Knowledge Base	• Lack of research, especially independent • Professionals are still formed traditionally based on linear models	• Generate more data to have a more complete understanding of current situation, practices, etc. • Support think-tanks to facilitate circular business designs	• Research of eco-designs • Introduction of circularity in schools and university curriculum

Institutional Support	• Slow, complex and rigid environmental impact assessment and licensing procedures • Outdated legislation, slow to modify and publish • Tax legislation – waste collection contribution • Lack of information distribution across and within institutions • Difficulty adding ideas to existing political agendas • Disconnection between food security and organic waste management • Unequal waste management capacities linked to municipal financial disparities	• Develop a systemic planning approach / script that integrates environmental, economic and health challenges • Introduce nutrient circularity into national, regional and local planning and policies • Develop alternative financing models and incentives to support recovery and decrease waste production • Develop indicators that can connect all actors • Review and update legislation regarding infrastructure & licenses	• Regional government can gather key actors • SEREMIs MMA and Salud can coordinate institutional efforts • Incorporate nutrient circularity into the National Soil Policy (Politica Nacional de Suelos) • Financial incentives through subsidies & R+D funding • Stricter recycling norms • Pilot projects specifically for recovered bio-input products • Include nutrient circularity in the Circular Economy Road Map of the MRSC • Establish and promote standardization and certification

C. Contextualization: Stakeholder interviews

	Challenges	**Opportunities**
Material Potential	• Animal excretions have a high recovery rate, but due to their minimal processing, also produce many externalities • Farmers do not or minimally assess their soil nutrients, since regulations don't require this • Almost all urban organic solid waste is destined to landfills • High land costs and restricting regulations limit the installation of new composting plants (urbanization) • High costs, lack of technology and few incentives limit waste treatment / reuse • Public green areas throughout the MRSC are usually very degraded with little maintenance	• The prohibition of burning of crop waste has improved the reincorporation to soil • Food industry byproducts are mostly recovered and reused as bio inputs, either through Armony (composting plant) or to croplands
Value Chain Characteristics	• Farmers resist changing their fertilization schemes • Small farmers and coops are focused on the survival of their business, with few resources for changes	• Growing interest in circular business models and waste revalorization

	• Farmers do not value and/or trust organic products • No consistent, known spaces for actors to exchange about nutrient circularity strategies • International exportation companies require, promote or prohibit the use of certain products • Little trust or exchanges between sectors and contexts (urban-rural)	• Growing interest in alternative bio-inputs, linked to high and fluctuating costs of chemical fertilizers • Increase in start-ups focused on recovery and reuse of organic waste in the region • Medium-sized farmers are an important group to prioritize (those that exceed INDAP limits)
Knowledge Base	• Lack of available information demonstrating efficiency of organic fertilizers • Lack of databases regarding byproducts, recovered/secondary materials, etc. • Guidance for farmer's come from INDAP workers or fertilizer merchants, who promote the use of chemical fertilizers and traditional practices • Agronomy careers in universities include little to no sustainable or circular agricultural knowledge • Few professionals trained in the use or production of bio-inputs • Most research is funded by private companies and not shared publicly (ex. Armony, FIA, CORFO) • Limited connection between academia/research and municipalities and/or companies	
Institutional Support	• Limited articulation between institutions in terms of nutrient-containing materials and nutrient circularity • Lack of and unequal distribution of municipal resources • Outdated regulations regarding soil quality, composting plant standards, bio input applications, etc. • Agricultural institutions are divided based on sectors, with little collaborations between them, and no circularity-centered groups • The management of public green areas is extremely variable and unequal across municipalities	• Key actors that can connect actors: ASCC, ODEPA, GORE • GORE has a working group for ENRO & circular waste management, but no consistent planning • ASCC has experience with successful cleaner production strategies with agricultural sector • Political frameworks for circularity include the REPP law and the ENRO • Increasing interest in sustainability and circularity in the agricultural institutions/agendas • Inter-sectoral roundtable for Circular Economy exists

D. Narrative 1

PURPOSE: The goal of this narrative is to improve the management of urban green areas using nutrient-containing secondary materials and products originating from organic municipal solid waste. This goal strongly resonates with the ENRO and the Circular Economy Regional Roadmap, aiming to increase recycling of this waste flow and allocate recovered nutrients to public green areas.

CONTEXT: This narrative unfolds in the short term, within the next 5 years, focusing on urban areas of the Metropolitan Region of Santiago. It considers the urban surface area identified in the spatial analysis of the diagnostic. In terms of the agri-food-waste subsystems, the narrative emphasizes the Commerce and Consumption (CC) and Treatment and Recycling (TR) subsystems. Most CC activities are concentrated in urban areas, while TR activities are primarily located in the peripheries. Within the CC subsystem, the primary flow of loss consists of food and garden waste destined for landfills, predominantly originating from households. Currently, there is minimal connection between TR industries and this waste flow, with the exception of garden waste from one municipality in the Region.

ACTORS: The main institutional actors in this narrative are the municipalities, the Ministry of Environment (MMA), and the Ministry of Housing and Urbanism (MinVU). The municipalities play a crucial role in environmental and green area management, often grouped together. The MA and MinVU are pivotal through their SEREMIs (regional ministry representatives). Two other institutional actors are essential to this narrative: the Regional Government (GORE) and the Health Ministry (Min Salud). The Regional Government's focus will be crucial for territorial planning aspects, while the Health Ministry and its SEREMI will play a vital role in establishing the regulatory framework. Though playing a minor role in this narrative, the Ministry of Agriculture (MinAgri) must be included to foster connections between rural and urban-focused actors and activities, emphasizing the quality and use of nutrient-containing secondary products. Finally, key material roles are held by providers of landscaping services, composting organizations and industries, and citizens represented through neighborhood associations.

VARIABLES: The storyline within this narrative can be described as two parts of a whole: the recovery of organic solid waste and the reuse of secondary materials or products. While these differentiated aspects help organize policies and strategies, the complementary nature of these actions is acknowledged and incorporated into policy documents. These documents specifically refer to nutrient resources and cycles to align diverse actors with a common goal. For the recovery aspect, both the Ministry of Environment’s SEREMI and municipal waste management departments play key roles in establishing action plans and mobilizing resources. This step is currently underway in many municipalities. However, important barriers regarding municipal technical and financial capacities remain, reinforcing the need for close collaboration between these two actors. Following the successful example of the Pintana Municipality, this narrative prioritizes separate waste collection systems. This strategy also involves reinforcing citizen awareness regarding separation practices and establishing a logistical procedure for the collection, transportation, and deposition of these materials.

When considering the treatment of these recovered materials, two additional key actors are the Regional Government and the Health Ministry. The Regional Government assesses appropriate locations for waste treatment and recycling activities, collaborating with MinVu and its SEREMI, the MMA and its SEREMI, and municipal authorities. Meanwhile, the Health Ministry and its SEREMI play pivotal roles with regulatory oversight, as sanitary legislation concerning waste treatment activities falls within their jurisdiction. Similarly, the MMA and its SEREMI adapt their regulatory frameworks for environmental evaluation procedures related to TR activities. These adaptations satisfy and comply with preventing and mitigating sanitary and environmental risks, while ensuring a feasible process for required TR projects. Considering the existing industries in the area and preferences expressed in current policy documents and strategies, this narrative prioritizes the use of aerobic composting technologies. This technology has been extensively studied, enhancing its technical feasibility and complementing the existing knowledge base. This includes both large industrial plants and smaller-scale options known as "campos de compostaje" located near urban centers, providing technically feasible treatment options.

When considering the reuse aspect of this narrative, the Housing and Urban Development Ministry (MinVu) is vital. Working closely with municipal green area management departments, they determine

and apply criteria to green area management protocols, including contractor procurement. These criteria include requirements for the use of secondary materials/products for fertilization and a recovery process for green waste generated from maintenance. MinVU offers periodic training for landscaping providers on the use of secondary materials/products and recycling practices for green waste. This training becomes required or favorable for public tenders. In parallel, the Ministry of Agriculture works closely with the Ministry of Health to develop a standardization and certification process for compost from municipal organic waste. This process allows users to trust the nutrient content and sanitary characteristics of the product, while also considering the final costs associated with the product in terms of market values. This collaboration is especially vital because it incorporates the Ministry of Agriculture, which is currently distanced from these strategies and policies. Similarly to MinVU, MinAgri offers periodic training on the use of secondary materials/products for both urban and rural farms, initially focusing on small/subsistence farms. Considering the technical and financial deficiencies of most municipalities, national institutions fill gaps in terms of capacity building activities and co-design of policies and protocols. Similarly, TR collection and treatment projects receive financial incentives from national and/or regional government funding. Additionally, the Regional Government (GORE) and MA provide financial support and incentives for research and development, as well as start-ups focusing specifically on technological and business innovations for the recovery and reuse of nutrient-containing materials in urban areas.

IMPLICATIONS: This narrative highlights opportunities to close nutrient cycles in mostly urban settings. It closely aligns with the ENRO framework but emphasizes the 'reduce demand' and 'increase reuse' goals of nutrient circularity. The beneficial outcomes include reducing waste sent to landfills and improving vegetative landscaping in public green areas. This narrative also aims to strengthen the market for secondary organic materials such as compost, soil improvers, and fertilizers. However, the success of this approach heavily depends on political will at all levels of governance, which influences resource allocation and action prioritization. Effectiveness also hinges on integrating these strategies with existing municipal territorial development plans and procurement protocols. There is a trade-off between decentralized, on-site waste treatment, currently promoted in multiple municipalities for smaller cascading of resources, and more centralized interventions. A significant uncertainty lies in the potential influence of landfill companies on municipalities, a relationship often politically and financially complex. Additionally, community reactions near TR projects should be addressed proactively through effective community engagement and communication strategies during project design and implementation. Finally, it's crucial to consider that while short-term interventions should strengthen the knowledge base and provide institutional support through capacity building, regulations, and incentives, a prolonged adjustment period is necessary. Planning for this period will be crucial for improving waste separation quality, thereby impacting material flow potential and value chain dynamics.

E. Narrative 2

PURPOSE: The objective of this narrative is to enhance nutrient cycles between the CP and AP subsystems by improving the recovery and reuse of animal tissue and manure. The objective is to increase the sustainability of agricultural activities by reducing emissions, contamination, and fertilizer demand, thereby enhancing food security in the region. These goals are aligned with objectives outlined in the three previously reviewed agricultural planning documents.

CONTEXT: This narrative focuses on changes within the private sector, deeming a medium-term period most appropriate. However, some changes, particularly technological interventions, occur in the short term. Within the CP subsystem, significant emphasis will be placed on the fruit production sector, with considerations also given to cereal and vegetable production. In the AP subsystem, the focus will be on swine and poultry production, where animal manure and tissue are key material flows. Currently, animal manures are primarily recovered by the same AP industries that produce them, and are reused for crop production, predominantly cereals and to a lesser extent vegetables, with minimal treatment. Meanwhile, tissues are recovered by rendering industries, which produced secondary products such as blood flours and animal fats, which are utilized for animal feed and organic crop production. Meanwhile, farmers across all crop types heavily rely on both imported mineral fertilizers and organic alternatives.

ACTORS: The main actor responsible for planning and administering resources is the Ministry of Agriculture (MinAgri), along with its regional representatives through the SEREMI, and the municipalities in rural areas. The SEREMI will play a key role in coordinating efforts, alongside the Regional Government (GORE). Several departments within MinAgri will provide crucial advisory roles, including INDAP, ODEPA, and INIA, alongside institutions such as the ASCC, local universities, and biotech companies. Key material actors include agricultural producers themselves, both in crop and animal sectors, represented through sectoral associations and cooperatives. There is a particular focus on medium-sized farms that do not qualify for INDAP assistance. These farmers possess sufficient technical and financial capacity to be receptive to innovations and may be less affected by international requirements compared to large-scale farms. Additionally, rendering plants and other biorefineries are significant players.

VARIABLES: This narrative relies on modifying variables linked to two key aspects: local knowledge base and nutrient recycling technology. In essence, animal manure undergoes deeper refinement, producing higher quality secondary materials. This occurs through a) larger animal farms with their own enhanced treatment equipment and b) new biorefineries specifically managing animal waste, which recover and treat these wastes to produce high-quality secondary materials. First, a working group is established by the Ministry of Agriculture specifically to promote circular practices in agriculture, initially focusing on connecting AP and CP activities. This working group includes representatives from all the actors listed in the previous section and explores and further develops the strategies mentioned in this narrative.

To reduce losses, legislation regarding soil quality expands to include nutrient content monitoring, following the trend of many European frameworks. This encourages nutrient use efficiency and decreases the risk of contamination. Publicly funded research supports this effort by identifying and mapping areas of nutrient saturation and depletion. In regulating soil nutrient content, many productive industries choose alternative treatment options for their waste materials, replacing their current low-treatment strategies. Livestock farms find safe alternatives for animal manure and are incentivized to adopt circular practices and technologies. Best practices developed by the ASCC with sectoral organizations, under the careful oversight of SAG, update to consider a wider range of technologies for circular resource management of animal farm wastes, including options for both small and large installations. MinAgri provides financial subsidies to farms and organizations for adopting these practices and related technologies. The adoption of circular practices is also rewarded with financial tax incentives and a recognition system that identifies sustainable businesses for local and international markets.

For AP farms that cannot or do not wish to adopt these best practices and technological upgrades, an alternative is to have an external biorefinery organization manage their waste. Biorefineries, including recycling and bio-tech start-ups, working with animal waste (manure and animal tissues) receive significant support from institutions such as FIA and CORFO for R&D to meet technical and safety standards and for scaling up their operations. Research on business models is also supported, aiming to address the demand for improved waste treatment from existing AP activities and for high-quality fertilizers from CP activities. Considering the wide variety of crop types in the region, development of specialized organic products is also encouraged. For well-established biorefinery industries, such as large rendering plants, support is provided for expanding their operations to new locations and products. As with the best practices funding, TR industries receiving public funds regularly share non-confidential information with research institutions to assess the use of these products and to promote continuous improvements and innovations. A database of organic secondary products meeting pre-established safety and technical standards is developed and managed by SAG and promoted to sectoral organizations.

To increase the reuse of recovered materials and products, it is vital to strengthen the regional knowledge base related to the use of organic secondary materials and products through research and capacity building initiatives. The Ministry of Agriculture allocates resources specifically for researching the use of organic secondary products in local agri-food activities, collaborating closely with INIA and local universities to ensure research findings remain publicly available. Priority is given to fruit production products and practices due to their regional significance, with efforts focused on fostering

collaborations with sector organizations. Simultaneously, public funding supporting private agricultural research requires incorporation of sustainable practices and the dissemination of non-confidential findings. Financial incentives are also provided to private organizations that conduct training and disseminate knowledge, such as seminars organized by recycling industries and biotech companies. The MinAgri SEREMI coordinates with INDAP and rural municipalities to develop and deliver courses on circular agriculture for farmers, environmental managers, agricultural extensionists, and agro-industry merchants, promoting the use of organic secondary products instead of imported mineral ones. Universities offering agricultural programs are encouraged to integrate circular agriculture information and practices into their curricula, enhancing their access to national grants and fostering collaborations with local institutions for training and project development.

IMPLICATIONS: This narrative focuses on increasing circularity in rural areas, where AP and CP production activities are concentrated. Beneficial outcomes include reduced dependency on imported fertilizers, both mineral and organic, strengthening the resilience of regional and local agri-food systems. Improved waste management decreases contamination, particularly in waterbodies, and supports and expands the local biorefinery sector to enhance resource recovery and revalorization. This narrative is dependent on collaboration and trust among actors, relying on an understanding that information sharing and collective action will lead to benefits for the entire agri-food system. Moreover, political will for resource allocation and strategy prioritization is crucial for success but is influenced by international agrifood markets and powerful fertilizer industries with conflicting interests. Uncertainties include the future of agricultural activities in the Metropolitan Region amidst urbanization challenges. Zoning considerations may also impact biorefinery installation or expansion, though less restrictive in rural areas than in urban areas. Additionally, this narrative is dependent on farmer acceptance and capacity, which vary across crop types and farm characteristics. To compete in the agro-industry market, recovered product quality and price must convince producers. Finally, there's a trade-off where pressures on animal waste management could potentially diminish small farm viability, despite the strategies outlined in this narrative.

F. Narrative 3

PURPOSE: This narrative's objective is to reconnect nutrients from households to food production, bridging urban and rural areas to close nutrient cycles on a more systemic level. More specifically, the goal is to recover nutrients from domestic wastewater through enhanced nutrient-recycling technology, resulting in secondary organic products suitable for food crops. This aims to decrease the loss of nutrients to waterbodies and landfills, while also improving the resilience of crop production in the region by reducing dependency on imported nutrient products. This narrative coincides with the goals of the local WWTP, but local authorities have shown limited interest in making progress in this direction.

CONTEXT: Given the magnitude of changes, the significant risks involved, and the departure from current interests and strategies, this ambitious narrative requires long-term planning. The main subsystems of interest are TP and CP, and more specifically, wastewater treatment and fruit and vegetable farming activities. Domestic wastewater represents the largest source of nutrient loss in the region, primarily lost through treatment processes and subsequent discharges. To decrease nutrient imports in crop production, focusing on reducing fruit and vegetable fertilizers is vital, especially for nitrogen and potassium supplied by mineral fertilizers. Currently, most WWTP sludge undergoes minimal processing and is primarily applied to industrial crop soils, predominantly maize. Approximately 20% of the sludge is directed to a monofil, where it undergoes aerobic digestion and stabilization, but is not currently reused, despite reaching high-quality standards.

ACTORS: This narrative necessitates the intricate collaboration of the Ministries of Environment, Agriculture, and Health to bridge urban-rural dynamics. Urban wastewater falls under the monitoring and regulation of the Ministry of Environment's Superintendencia del Servicios Sanitarios (SISS) and the Ministry of Health's Environmental Health Department. Meanwhile, crop input product standards are regulated by the Ministry of Agriculture's Servicio Agricola Ganadero (SAG). Other key institutions within the Ministry of Agriculture, such as INDAP, ODEPA, and INIA, play important advisory and coordinating roles, along with the regional SEREMIs of all three ministries. Key material actors include wastewater

treatment plants (WWTPs), biotech and biorefinery companies focusing on domestic wastewater, and crop producers, represented through sectoral associations. Additionally, food industries and associations, such as ChileAlimentos, are crucial to this narrative.

VARIABLES: As with other narratives, activities focus on two aspects: improving recycling technology and increasing the reuse of secondary materials in agriculture. First, following the example of European frameworks, soil quality legislation is revised to include nutrient content monitoring and limitations, promoting nutrient use efficiency and reducing the risk of contamination from overfertilization.

Similarly to Narrative 2, this change triggers modifications in waste management practices at WWTPs, specifically concerning sludge. Before expanding the application of these secondary materials, their quality is enhanced through further treatment. Aguas Andinas (the main WWTP company in the Metropolitan Region) first assesses and selects possible technological interventions and plans their implementation across their many existing WWTPs. This technological innovation plan is supported by publicly funded research projects with local research institutions, such as INIA and universities, while being closely supervised and regulated by the MinSAL and MMA SEREMIs as well as SAG. Nutrient recycling technologies are gradually incorporated to a) increase the recovery of nutrients from wastewater, such as by cultivating microalgae or using nanofiltration to concentrate nutrients in sludge, and b) transform sludge into higher-quality secondary products through technologies such as ammonia stripping and struvite precipitation, producing high-quality, concentrated, sanitary, and practical products like granules or pellets. Collaborations also arise with other biorefineries, such as composting plants, to mix sludge with other biomass materials, producing stable and nutrient-rich secondary products. The quality of these secondary products is extensively studied and reviewed to ensure both sanitary and technical standards, which is then certified by SAG for use in food crop production, such as fruits and vegetables. Regulations for the use and application of secondary products from WWTPs are updated, based on examples such as the European Union's Directive 86/278/EEC, with guidelines for periods and methods of application for fruit and vegetable croplands. To increase the use of these recovered secondary products and materials, the same strategies proposed in Narrative 2 are applicable:

- MinAgri allocates resources for research and pilot projects related to the use of secondary products from WWTP, prioritizing fruit and vegetable production and collaborations with the private sector.
- Publicly funded agricultural research for the private sector regarding WWTP outputs or the use of secondary products requires sustainable practices and dissemination of non-confidential findings.
- Financial subsidies are provided to Aguas Andinas for training and knowledge dissemination (such as courses and seminars) regarding the use of their secondary products.
- MinAgri SEREMI coordinates with INDAP and rural municipalities to develop and deliver courses on circular agriculture, promoting the use of secondary products.
- Universities are encouraged to integrate circular agriculture information and practices into their curricula, improving their access to national grants and collaborations with organizations.

Public relations and communication receive special attention, from the beginning of this narrative. Collaboration with the food industry sector is vital, as they serve as key intermediaries between farmers and consumers. Sufficient resources are allocated to establish a comprehensive communication plan that includes focus groups, workshops, and seminars. These efforts aim to effectively disseminate information about secondary products from WWTP to the general public, build consumer trust, and promote the adoption of these products. The communication strategy also seeks to educate the public on the environmental and economic benefits of using secondary products, thereby fostering a positive perception and encouraging widespread acceptance.

IMPLICATIONS:

This narrative enables the increased recovery of nutrients from the region's most significant waste flow, thereby closing or reducing a critical nutrient loop. It fosters collaboration between traditionally separate actors, now united in valuing nutrients recovered from urban households and reused on rural farms. While many countries have made significant strides in nutrient recycling technology, such initiatives remain rare in the country and Latin America, aside from small-scale research projects. Consequently, there will likely be considerable resistance and concern about allocating public funds to implement this

narrative, underscoring the importance of strengthening the R&D component. Building and fostering international cooperation will be crucial for the successful development and implementation of these strategies. This narrative relies on the acceptance and trust of *all* stakeholders in the agri-food-waste system, a complex aspect requiring meticulous planning in communication and public relations, particularly regarding sanitary characteristics. The international agrifood market also influences this narrative and may hinder the adoption of secondary products. However, global trends toward increasing circular resource management and addressing food security risks posed by climate change may lead to these limitations shifting over time, reinforcing the need for long-term planning. Additionally, for some WWTPs, producing biogas may be necessary for the feasibility of technological innovations, thus trading off nutrient recovery for alternative energy production.

5. DISCUSSION & CONCLUSION

Cities and metropolitan areas play a pivotal role in advancing sustainable development, which is a key focus of both urban metabolism and urban planning. These efforts frequently align with global frameworks like circular economy and bioeconomy, particularly in response to SDG 11 (‘Sustainable Cities and Communities’) and SDG 12 (‘Responsible Consumption and Production’), both of which highlight the importance of sustainable material flow management within urban territories (Ellen MacArthur Foundation, 2019). However, effectively integrating these frameworks into practical urban development remains a significant challenge, especially when it comes to managing nutrient-containing materials such as fertilizers, food, and organic waste. These flows are essential in addressing planetary boundaries, including nitrogen and phosphorus exceedance, as well as mitigating climate change. As cities grow and aim for greater sustainability and resilience, their approaches to managing these critical flows often lack coherence and effectiveness.

This research was designed to systematically analyze nutrient flows from a regional perspective, with the aim of contributing to strategic planning processes that promote greater nutrient circularity. The focus was on South America, a region selected for its critical role in global agrifood production and its rapidly urbanizing landscape, both of which present unique opportunities and challenges for enhancing nutrient management.

The initial step in addressing nutrient circularity involved identifying the factors that influence the management of nutrient-containing flows and determining how these factors could be measured. We first aimed to define and quantify the **nutrient circularity capacity**, which refers to the potential of a specific context or area to develop and implement circular nutrient management strategies based on its existing characteristics. To achieve this, this study identified the material and organizational or social factors influencing nutrient circularity capacity (NCC) and linked them to relevant indicators. These indicators were then subjected to a multicriteria analysis to identify the most suitable options based on feasibility, salience, and credibility. The framework was subsequently applied to various South American metropolitan areas, facilitating a comparative analysis between them.

The next step was to determine how a specific city or region could conduct a comprehensive, planning-oriented assessment of these factors. To address this, we developed a strategic, multi-dimensional **diagnostic** tool aimed at assessing the management of nutrient resources from a territorial perspective. This tool integrated principles and methods from urban metabolism and urban planning. The process involved extensive data collection, stakeholder interviews, and analyses of spatial, material, and socio-economic factors across the agri-food-

waste system in the studied area, the Metropolitan Region of Santiago (MRSC), a regional leader in nutrient circularity capacity.

In the third step, aiming towards incorporating nutrient circularity into ongoing or future strategic planning processes, it was crucial to integrate and synthesize the diagnostic findings with existing policies, strategies, and stakeholder interests and concerns. This step aimed to bridge the gap between the territorial nutrient-flow diagnosis and scenario building by developing **narratives** that reflected the collective analysis of relevant and diverse stakeholders. We proposed a framework that combined diagnosis insights with stakeholder inputs and local policies to create these narratives, offering an evidence-based and contextualized perspective on nutrient circularity. This approach was designed to support practitioners in current and future scenario-building processes and vision exploration exercises in the context of circular urban development. As with the previous diagnosis framework, the framework was applied to the MRSC as a case study.

5.1. Summary of Findings

5.1.1. Nutrient Circularity Capacity

This study identified 12 influencing factors across four central themes that affect nutrient circularity capacity (NCC) from a global perspective. To quantify NCC within South American Metropolitan Areas (SAMAs), 11 indicators were identified and/or developed. These indicators were selected based on their salience, credibility, legitimacy, and feasibility, comprising six indicators focused on existing data for organizational factors and five formulated values for material factors.

NCC was measured and compared across nine of the largest metropolitan areas in South America. The findings indicated that Uruguay exhibited the highest organizational NCC, whereas Paraguay and Bolivia demonstrated the lowest levels. In terms of material NCC, Santiago (Chile), Montevideo (Uruguay), and Santa Cruz (Bolivia) were ranked highest, while Asunción (Paraguay) was ranked the lowest. Overall, Montevideo emerged as the leader in nutrient circularity capacity, closely followed by Santiago, while Asunción was identified as the least developed in this regard.

5.1.2. Multidimensional Strategic Diagnosis

A comprehensive diagnostic framework was developed to be both strategic and multidimensional, specifically focusing on the activities and stakeholders associated with nutrient circularity. This framework is strategic in that it provides selective, critical, and context-specific information, and multidimensional as it incorporates spatial, material, and social data

analyses. The framework involves several key steps: firstly, identifying the principal activities across the five subsystems of the agri-food-waste system within a defined area; secondly, determining the main nutrient flows and quantifying their nitrogen, phosphorus, and potassium (NPK) content; thirdly, geographically mapping these activities, their flows, and the associated stakeholders; and finally, characterizing these stakeholders based on their primary interests or concerns, the subsystems they are associated with, and their roles within the agri-food-waste system.

To synthesize this information, the framework proposes two indicators that correspond to the primary objectives of nutrient circularity in metropolitan areas: the first focuses on the **recovery of urban nutrients** (RUN), aiming to minimize nutrient losses, and the second emphasizes the **reuse of recovered nutrients in agriculture** (RNA), with the goal of reducing the demand for raw materials.

5.1.3. Scenario Narratives

An innovative framework was proposed to develop scenario **narratives** grounded in diagnostic findings, local policy priorities, and stakeholder perceptions, all within the overarching principle of nutrient circularity. This framework offered a clear and reproducible methodology that can connect the assessment and planning phases within urban planning processes, effectively linking pre-existing and implemented principles and tools. To enhance the relevance, legitimacy, and feasibility of the results, multiple instances of stakeholder interactions were integrated throughout the process. Specifically, this methodology combined insights from scientific analyses, political documents, and stakeholder perceptions to identify overlaps and gaps, which served as a foundation for constructing comprehensive narratives to guide scenario exploration exercises.

The framework comprised three primary steps: 1) contextualization, 2) synthesization, and 3) narrative construction. In the synthesization step, the framework introduced a transparent and systematic method for categorizing concepts, ensuring alignment with the systemic characteristics and principles of nutrient circularity. This approach formed the basis for narrative development, adopting a systemic, comprehensive, and strategic perspective. Scenario narratives were developed by respecting all the essential elements of the concept, effectively connecting identified components: purpose, context, actors, variables, and outcomes into a concise yet comprehensive storyline. This method ensured that the narratives were coherent and holistic, serving as valuable tools for scenario exploration and strategic planning in urban development contexts.

5.1.4. Case Study Reflections

The application of the NCC framework to South American metropolitan areas provided a concise assessment that facilitates comparisons across cities and regions, stimulating further discussions and future analyses. The NCC assessment provided insights indicating that the MRSC was one of the leading regions in nutrient circularity, ranking second in the region. This position was largely due to strong performance in indicators related to animal production, wastewater and sludge management, and relevant existing policies such as its National Circular Economy Policy.

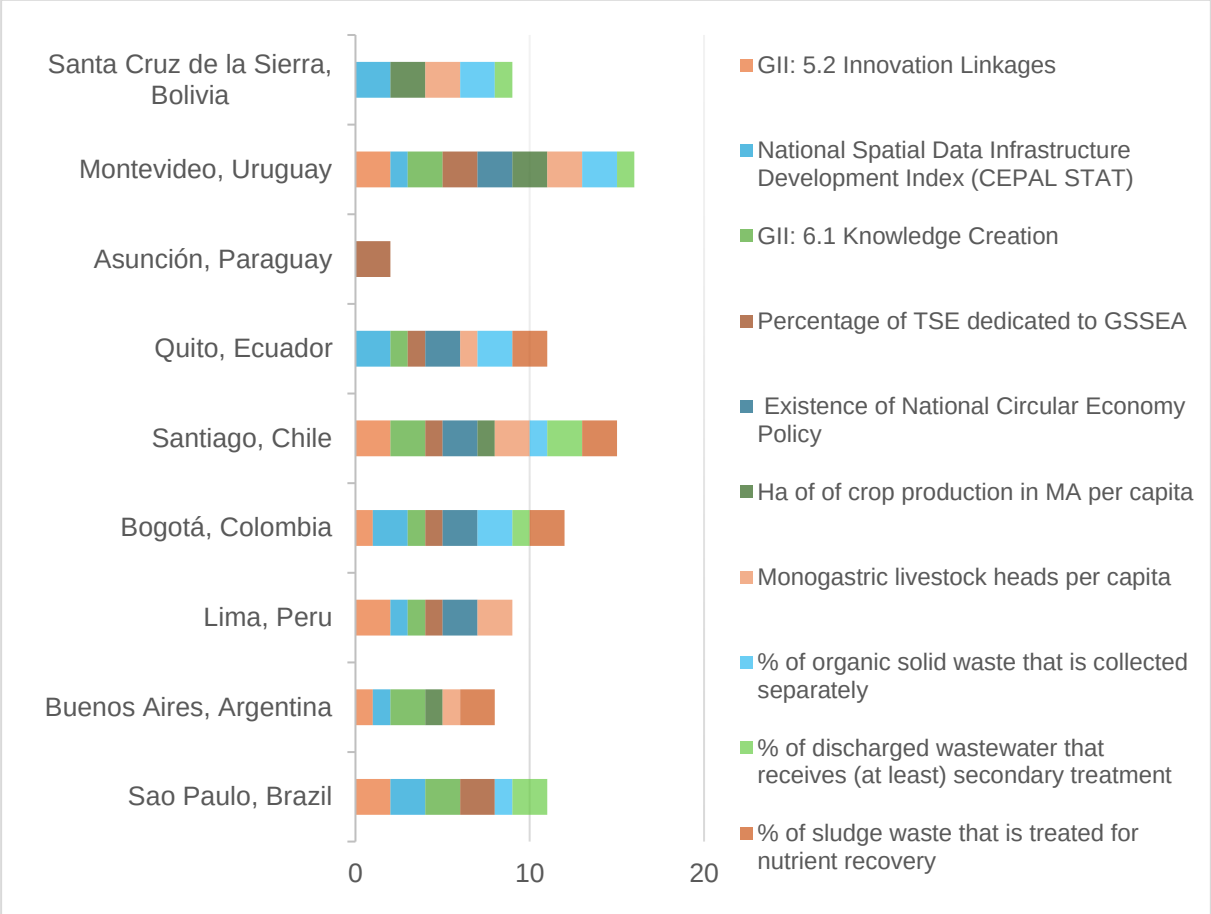

Figure 1. Nutrient Circularity Capacity Scores for South American Metropolitan Areas. (Fleitas et al. 2023)

The strategic multidimensional diagnostic identified the main activities within the agri-food-waste system in the MRSC, including their associated flows and key actors. The locations of these activities were mapped, offering insights into distribution and spatial patterns. The nitrogen, phosphorus, and potassium (NPK) content of these flows was quantified, providing valuable data on the system's main losses, recoveries, reuse, and imports. By combining this information into heatmaps, areas of nutrient surplus or deficiency across the region were

identified. Key actors associated with these activities and flows were also identified and characterized.

The RUN indicator scores showed a recovery rate of 72% for N+P+K, driven primarily by wastewater treatment, while the RNA indicator revealed much lower nutrient reuse rates at 12% for these three macronutrients. The findings from this diagnosis suggest that improving these indicators requires increasing the recovery of organic solid waste, such as food and garden waste currently sent to landfills, and enhancing nutrient reuse by addressing regulatory restrictions on the use of animal excretion and wastewater treatment plant sludge, overcoming technological barriers to retaining nutrients in secondary materials, and promoting greater adoption of organic fertilizers by farmers.

A review of policy documents revealed two overarching goals prevalent across policies in the MRSC: 1) increasing the recycling of organic municipal waste and 2 promoting sustainable agricultural production. Stakeholder inputs further highlighted two notable insights shared by actors across sectors and landscapes: the need for improved territorial planning, particularly regarding the impact of urbanization on the feasibility of productive and treatment activities, and the absence of a nutrient-focused perspective, recognized as a critical link between urban and rural contexts. After synthesizing and categorizing over 180 variables and identifying overlaps and gaps, three focal questions were developed to comprehensively address all subsystems and objectives of nutrient circularity. The first two questions directly related to the previously identified shared goals, while the third aimed to address a key issue bridging rural and urban contexts. After incorporating stakeholder feedback, these questions were used to elaborate three narratives, summarized in the following table.

Table 1. Summary of Narratives presented in Chapter 4. (Own elaboration)

Summary of Narratives
1. Closing Urban Loops: The narrative seeks to restore and enhance Santiago's public green areas by using compost from household waste. This short-term initiative involves key actors, including various ministries, municipal authorities, composting industries, and neighborhood associations. Key variables include fertilization practices, waste management, transportation costs, land availability, and regulatory frameworks. The plan focuses on co-designing an action strategy, implementing waste separation systems, assessing composting locations, offering incentives, and building capacity among citizens and organizations. Expected benefits include closing urban nutrient cycles, reducing landfill waste, and strengthening the organic materials market. Challenges include political dependency, community reactions, and the need for integration with existing plans,

as well as uncertainties in municipal-landfill company relationships. A key trade-off is between decentralized and centralized waste treatment approaches.
2. Closing Loops in Agriculture: This narrative aims to boost nutrient reuse between animal and crop farms, reducing reliance on imported fertilizers. This medium-term initiative involves key actors like the Ministry of Agriculture, agricultural organizations, universities, municipalities, and rendering industries. Critical variables include fertilizer use, bio-input training, emissions, waste treatment technologies, and cross-sector collaboration. The plan includes establishing a multi-sector working group, integrating circular practices into education, expanding soil quality legislation, increasing research funding, and providing financial incentives for circular technologies. It also supports biorefineries and developing regulations for secondary products. Anticipated benefits include reduced fertilizer imports, stronger agri-food system resilience, improved waste management, and biorefinery growth. Challenges include political dependency, market influences, farmer acceptance, and small farm viability. Key uncertainties relate to biorefinery zoning and the future of agriculture in the region.
3. Connecting Urban and Rural Nutrient Cycles: The narrative aims to enhance food security by fertilizing fruit and vegetable crops with nutrients recovered from WWTPs. This long-term initiative involves key actors such as the Ministries of Agriculture, Environment, and Health, regional governments, WWTPs, crop farms, and biotech startups. Critical variables include fertilizer use, bio-input training, transportation costs, and collaboration between actors. The plan focuses on expanding soil quality legislation, integrating nutrient recycling technologies in WWTPs, supporting WWTP-biorefineries collaboration, and updating regulations for using secondary products in food crops. It also includes R&D for WWTP products, knowledge-sharing incentives, and integrating circular agriculture practices into education. Expected benefits include increased nutrient recovery, closing nutrient loops, reduced fertilizer imports, improved waste management, and greater agri-food system resilience. Risks involve political dependency, market influences, and trust issues across the agri-food system, with trade-offs like prioritizing biogas production and uncertainties around international cooperation and market acceptance of secondary products.

The resulting narratives successfully bridged gaps between subsystems, influencing factors, and nutrient circularity objectives, while also addressing elements that are overlooked or not prioritized in current plans.

5.2. Systemic Analysis for Strategic Nutrient Circularity Planning

This research was designed to systematically analyze regional nutrient flows to inform strategic planning processes that enhance nutrient circularity. As outlined earlier, the study was structured into three research phases, each of which provided independent value while also building progressively on the preceding phase to collectively address the overall research objective.



1. What are the factors we need to consider when analyzing and managing nutrient containing flows, and how can we measure them?
2. How can we assess these factors at a territorial level in a comprehensive yet planning-oriented way?
3. How do we synthesize and present these findings to be functional and constructive for strategic planning processes?

To conduct a systemic analysis, it was first necessary to identify, from a range of disciplines and sources, the key factors involved in analyzing and managing nutrient-containing flows, as well as to determine how these factors could be measured. This led to the identification of 12 Influencing Factors spanning material and social dimensions, and the development of a framework to select indicators of Nutrient Circularity Capacity (NCC)—the potential of a city or region to develop and implement nutrient circularity strategies. These factors served as a foundation for the future diagnosis and narrative development frameworks. The NCC assessment was applied to South American metropolitan areas, a region chosen for its critical role in global agrifood production and its rapidly urbanizing landscape, which present unique and urgent opportunities and challenges for improving nutrient management. This led to the identification of forerunners, which supported the selection of the case study for steps 2 and 3: the Metropolitan Region of Santiago.

Next, it was essential to establish how to assess these factors in a comprehensive, planning-oriented manner. Drawing on principles and methodologies from urban metabolism and urban planning, a multidimensional strategic diagnosis framework for nutrient flow management was developed, assessing factors across multiple dimensions. Applied to the Metropolitan Region of Santiago, this framework produced research outputs such as maps and Sankey diagrams. More importantly, the integration of spatial, material, and social analyses highlighted key strengths and weaknesses across the multiple factors influencing nutrient circularity in the region.

The final research step aimed to address the remaining aspect of the main objective: informing strategic urban planning processes. This required determining how to synthesize and present the gathered insights in a way that is both functional and constructive for planning. The outcome was a framework consisting of contextualization, synthesis, and the construction of narratives, all with a systemic perspective on nutrient circularity.

Each research step was built upon established principles, theories, methods, and insights from multiple disciplines, proposing innovative multidisciplinary tools designed to inform the

development of policies and plans that enhance nutrient circularity. The implications of these contributions for both scientists and practitioners are further explored in the following chapter.

5.2.1. Research

Much of the existing research on urban nutrient recovery and recycling has been concentrated in Europe and Asia. However, this study demonstrated significant potential to close nutrient cycles in many South American cities, suggesting a valuable area for further investigation. One area that future research can focus on is assessing whether the technologies and policies developed in other regions can be effectively applied in these important contexts. This is particularly relevant for the MRSC, where nutrient recovery from wastewater treatment plants is already high, managed by a single key actor.

That first step of this study, the identification of influencing factors of nutrient circularity, which span multiple dimensions and disciplines, formed the foundation for a more comprehensive and systemic approach to impact assessments, diagnosis, and scenario development. This was substantiated by the subsequent steps, which incorporated these factors throughout the research process to adopt a systemic perspective for subsequent diagnostic and narrative development steps. In its initial step of defining a strategic analysis, the diagnostic framework provided a novel and systematic method for cities and regions to identify key activities related to nutrient circularity within their geographical boundaries. This method takes advantage of widely available information, making it applicable across diverse contexts and useful for refining the focus of research, particularly in areas with a variety of activities.

Building on this, while the diagnostic framework represented a multidisciplinary approach by integrating perspectives and tools from different disciplines, the narrative development framework extended this to a transdisciplinary level. It not only utilized insights from multidisciplinary research but also incorporated political and stakeholder perspectives, thereby creating a new, integrative approach. The narrative development framework, particularly through its contextualization step, highlighted the critical importance of including stakeholder inputs in research. Certain variables, especially those related to social factors, are not readily identifiable in databases and literature, whether as barriers or opportunities. This underscores the necessity of engaging with a broad range of stakeholders across relevant subsystems, as their perspectives can differ significantly. Although this principle is a cornerstone in the social sciences, it is frequently overlooked or underestimated in the natural sciences, potentially resulting in important omissions.

In its synthesization step, the framework introduced a transparent, reproducible, and systematic method for categorizing concepts that align with the systemic characteristics and principles of nutrient circularity—a practice often missing in scenario analysis research. Moreover, the basis for this categorization, which considers influencing factors, subsystems, and priorities of nutrient circularity, can be applied to other data analysis frameworks addressing nutrient circularity.

5.2.2. Planning and Policy Development

This study emphasizes that nutrient circularity is an important but often overlooked component to two significant challenges that urban planners must address: the expansion of urban areas and the shrinking of agricultural land. Additionally, nutrient circularity is crucial in addressing two major policy concerns: urban waste and contamination, and food security and resilience. The research also underscores the importance of data availability for robust assessments and planning, emphasizing the need to integrate and enhance data generation, management, and dissemination in both current and future policies and plans.

The identification of Influencing Factors involved processing over 400 data elements from international and interdisciplinary literature, ultimately synthesizing 12 factors across 4 Central Themes. These factors enable actors from various contexts to consider the diverse dimensions and perspectives that influence their ability to improve the management of nutrient-containing flows. Through the indicator selection process, stakeholders can utilize credible existing information to measure and compare their capacities, identify gaps, and prioritize areas for further evaluation, thereby fostering the development of effective, informed policies and plans. This process allows for the adaptation of international theories to local experiences and data. While the indicator selection process may evolve as more information becomes available, the Influencing Factors remain the core structure guiding the assessment. Moreover, the results from the application of this assessment framework suggest that emphasizing the enhancement of organizational capacity may be particularly advantageous, as it is more directly actionable and can indirectly contribute to increased material capacity through improved environmental management and support for periurban agriculture.

Additionally, the diagnostic findings can offer valuable insights for planners and policymakers, enabling them to pinpoint priority areas that require further analysis and strategy development, as well as to identify key actors for collaboration. Furthermore, the nutrient-focused indicators developed in this study serve as a critical tool for measuring and communicating resource circularity on a systemic level across sectors and territories, while respecting the administrative and political distinctions between urban and rural development and management.

While narratives are widely used in planning processes, their development often appears subjective and opaque. The narrative construction methodology proposed here provides a more systematic and transparent approach, ensuring that narratives are contextualized, feasible, relevant to stakeholders, and address actual material and social priorities. The narrative framework's policy review step revealed a clear trend in planning and policy concerning nutrient circularity across many cities globally, validating the relevance of the indicators proposed in the diagnostic framework, which focus on the recovery of urban nutrients and the reuse of nutrients in agriculture. It also highlights the existing division in policies and strategies based on the rural-urban divide and confirms the current fragmentation or deficiency in strategies that often miss key challenges or opportunities related to existing material or social priorities for improved nutrient resource management.

Meanwhile, the method for synthesizing findings in the narrative development step can provide a valuable additional tool for advancing nutrient circularity in planning processes. It can lead to two significant outcomes: first, the identification of overlaps that can strengthen narratives by integrating strategies and actors; and second, the identification of gaps that need to be addressed in existing or new narratives, encouraging the exploration of options not currently present in existing plans. This narrative development method aims to produce zero-order narratives that can be directly integrated into scenario development and analysis processes undertaken by both urban planners and scientists.

5.2.3. Cities and Regions in South America

This assessment of Nutrient Circularity factors represents a novel approach in the South American context, a region characterized by significant urbanization. By comparing NCC across countries in South America, this study highlighted both similarities and differences, even among neighboring nations. These findings present opportunities for countries to learn from each other by identifying and implementing strategies that are effective in similar contexts. Furthermore, the comprehensive frameworks developed in this study have the potential to foster collaboration among researchers, planners, and local stakeholders, enhancing efforts toward nutrient circularity.

Urbanization has had, and will continue to have, a profound impact on agri-food-waste systems in South America. In the MRSC, for instance, urbanization has led to a decrease in agricultural activities and limited waste treatment options. Cities like Santiago function as major nutrient sinks, primarily through the accumulation of organic solid waste in peri-urban landfills and the discharge of treated wastewater. These dynamics present substantial challenges to nutrient recycling, which is a critical component of sustainable urban development. Although these

challenges are widely recognized, they remain inadequately addressed, largely due to the division of actors and strategies across different sectors.

Nutrients are a vital resource across all subsystems of the agri-food system, serving as both food products and inputs for productive processes. However, terms such as "organic waste" and "fertilizers," which describe key nutrient-containing materials, often reinforce the divide between sectors and actors identified in this research. A nutrient-centered perspective, as proposed by the proposed frameworks, can help bridge these divides by connecting stakeholders from both rural and urban contexts, which are currently fragmented by differing strategies and policies. While metrics for resources like energy and water are well-developed, those for nutrients remain underdeveloped, underscoring the need for more comprehensive evaluation tools. By integrating a nutrient-focused approach into existing evaluation and monitoring frameworks, stakeholders could foster a more cohesive and unified strategy for managing nutrient resources.

The diagnostic findings in the MRSC identified specific activities, locations, and actors that should be prioritized to achieve nutrient circularity goals. One critical insight from this research is the region's heavy reliance on imported fertilizers, combined with significant nutrient losses to soils and water bodies. These issues pose threats to food security and contribute to environmental contamination. This information can inform the development of more effective strategies and policies, such as revising regulations, creating targeted research and development programs, and fostering synergies within and between sectors. Additionally, the diagnostic highlighted key actors who are currently excluded from these efforts but should be included, as well as those who could be aligned toward common goals or concerns. It also underscored the importance of individuals and organizations that play crucial roles in connecting different sectors, emphasizing the need for a more inclusive and coordinated approach.

To effectively address these challenges, policies must be adapted to promote resource recovery and reuse in a safe and feasible manner, taking into account the specific challenges and opportunities identified by the frameworks proposed in this study. For the MRSC, this involves focusing on land use and soil regulations, treatment plant licensing, the application and quality of recovered materials and products, and financial incentives for the production and use of these recovered products. Furthermore, this research underscores the importance of knowledge creation and transfer in advancing nutrient circularity. While a significant amount of research and development (R&D) is conducted within the private sector, often with public

funding, there is a pressing need for greater efforts to disseminate information and transfer skills across relevant actors and sectors to enhance collective capacity and knowledge.

Lastly, the narrative development framework and findings of this study are particularly significant given the limited research on scenario building and exploration concerning regional or urban nutrient circularity in South America and the Global South more broadly. Urban planning processes in these regions are intensively underway to address the challenges posed by rapid urbanization, and the insights from this research provide urgently needed support for developing more sustainable and resilient cities. Considering this, the insights from this case study diagnosis and narratives could be valuable inputs for their ongoing assessments and scenario explorations, potentially without the need for a lengthy analysis, if the findings are effectively validated by relevant experts and local stakeholders.

5.3. Limitations & Future Work

5.3.1. Analysis scope & methods

Balancing systemic and comprehensive analyses is inherently challenging and requires careful consideration of which aspects demand what degree or scale of analysis. In its first step, this research did not address underlying influencing factors such as geographic, socioeconomic, and cultural aspects, which were beyond its scope. However, when an influencing factor is identified as particularly relevant for a city or region due to its strength or weakness, these aspects should be further explored in future studies for a more in-depth analysis.

Regarding the second research step, defining geographic boundaries for flow analyses posed a challenge, especially considering significant exchanges with neighboring cities and regions. In the MRSC, this issue was particularly evident for crop and animal production, which is shifting southward toward the adjacent department. Consequently, strategies aimed at achieving nutrient circularity may need to extend beyond the metropolitan region. While this diagnosis did not assess activities, flows, and actors in other regions, it is likely that there are overlaps in terms of the main challenges and opportunities, particularly in aspects like policies, which are often relevant at the national level. Additionally, operating within political and administrative boundaries has considerable advantages for planning processes. While this research feels that it effectively balanced these aspects, future studies should also consider how different scopes might affect outcomes.

For the narrative development, the policy document review was limited to recent regional or national-level documents. This focus was chosen because such documents typically set the foundation for more localized policies, and the outputs of this work are intended to guide

planning processes at a similar level. However, more localized planning documents, such as individual municipal plans, might also reveal important variables. These could be included in future diagnostic or scenario exploration steps at a more localized level. In addition, for this step's synthesization substep, variables from multiple sources were considered to be of equal importance. Future research could explore organizing these variables according to different criteria, assessing the relative importance or impact of inputs from scientific analyses, institutional documents, and stakeholder perspectives on narrative development.

This work developed three focal questions and subsequent narratives based on the overlaps and gaps identified through the synthesis and categorization of variables. This number was deemed sufficient to cover the subsystems and priorities of nutrient circularity and to test and validate the proposed framework. However, despite efforts to minimize ambiguity, some subjectivity remains in this step, and the number or nature of focal questions may vary. It is important to consider balancing narrative scopes with the nature of planning processes, which often require reasonable, strategic simplifications.

Finally, this study primarily focused on nutrient recovery and reuse, without addressing other crucial aspects like reducing demand and nutrient losses through improved agricultural efficiency, dietary shifts, etc., which are also essential for shrinking nutrient cycles. Research on agricultural input efficiency is abundant, often tied to technological interventions, and is based on the actual nutrient needs of specific crops. In this study, this was incorporated into the flow analysis using local technical best practice guides for each crop. Additionally, nutrient demand is influenced by the reuse of materials from recovered nutrients. Like fertilizer efficiency, losses in crop production and food processing are also abundantly researched, driven by economic interests in yield and productivity, which are primarily agricultural interests.

Human food demand, influenced by factors like cultural practices and personal finances, plays a crucial role in nutrient cycles. However, changing food demand is socially complex and may negatively impact local economies, making it a lower priority for practitioners. Meanwhile, reducing food losses in commerce and consumption is also important, particularly for improving food security among vulnerable groups. However, since most nutrients in this subsystem are found in wastewater after food consumption, this study suggests that focusing on nutrient recovery from wastewater may be more effective than targeting organic solid waste reduction, especially given the substantial technological and economic challenges associated with the latter in South America. Nonetheless, exploring these complementary areas remains essential for developing systemic strategies to shrink and close nutrient cycles, particularly in

future scenarios where immediate priorities have been addressed, as seen in European contexts.

5.3.2. Stakeholder interactions & Data Availability

The indicators used in the NCC assessment were heavily dependent on their feasibility, which was closely linked to data availability and quality. As a result, the assessment was limited by the data that could be obtained. These indicators can and should be modified in contexts with higher data availability to improve accuracy and relevance.

While assumptions and modeling were minimized as much as possible, the lack of data necessitated their use for certain flows, particularly those related to recovered materials and products such as compost and biofertilizers. Efforts were made to validate these assumptions to reduce the risk of underestimating or overestimating the reuse of these materials in agriculture.

For the narrative development step, maintaining a systemic perspective requires the inclusion of inputs from all subsystems and main activities. However, this is not always feasible due to data limitations. In the case study, stakeholder inputs were missing from certain subsystems and activities, such as the food and feed processing industries in the region. Despite these gaps, the use of multiple sources of variable inputs, including diagnostic analyses and policy documents, helped mitigate the impact of such exclusions. This approach ensured a more comprehensive understanding of nutrient circularity, even when direct stakeholder input was not available for all relevant areas.

5.3.3. Existing & future planning processes in SAMAs

In this research, the MRSC was selected as it was identified as a forerunner in Nutrient Circularity Capacity within the region, offering a potential model for other countries and cities in South America to enhance nutrient circularity. Although Chile, and particularly Santiago, differs significantly from many other South American metropolitan areas (SAMAs) due to its relatively high GDP per capita and advanced wastewater treatment industry, the findings from Santiago's diagnosis still provide valuable insights for other cities and regions. This is especially true for cities like Montevideo (Uruguay) and São Paulo (Brazil), which also have higher GDPs and more developed wastewater infrastructure. Other South American cities, despite differing rates of wastewater collection, can also benefit from focusing on improving WWTP technologies and increasing the separate collection of organic solid waste, which remains low across the continent. Furthermore, the trend of declining agricultural activities due to urbanization is one that many cities in the region are likely to experience. The policy review

in the third research chapter also confirms a global pattern of separating goals and strategies between urban and rural contexts. As a result, the narratives developed for Santiago could provide valuable guidance to other areas, particularly those with significant surrounding agricultural activity.

It is also important to note that the unequal distribution of resources and funds among municipalities is a significant barrier to increasing nutrient recovery from solid waste in Chile. Addressing this issue requires a closer examination of the larger political and socioeconomic frameworks, which are currently quite fragile and volatile. This presents both challenges and opportunities for improving nutrient recovery, but it demands a more in-depth analysis to fully understand the implications. Data availability is another critical factor in this context. A key data source for the diagnostic of step 2 was the Pollutant Release and Transfer Register (known as RETC in Spanish), which, while part of an international framework, is not yet widely implemented across South America . This highlights the challenges and opportunities associated with data collection and usage in the region. This framework was particularly important for quantifying flows from Food & Feed Processing Industries, Waste Treatment & Recycling plants, and some activities within the Commerce & Consumption subsystem. In countries without an RETC database, alternative data sources could include environmental license evaluations, which are usually publicly available, or interviews with sectoral organizations or private waste management industries. Locations which were obtained from the RETC database could be identified using these same sources.

The outcomes of this study, including the diagnostic and narratives, are intended to contribute to broader assessments and planning processes for circular resource management and sustainable urban development. Future research should investigate how nutrient circularity narratives can be integrated with other resource circularity narratives during scenario development to identify potential synergies and conflicts. Additionally, further analysis at the subsystem level could refine the framework for developing more targeted narratives for each subsystem.

This study intentionally concludes with "zero-order" qualitative narratives, which are designed to be comprehensive enough to guide future scenario building through robust yet adaptable stories. In subsequent steps, these narratives should be quantified following the "story and simulation" approach, and iteratively reviewed and refined before being shared with a broader audience.



Figure 2. Status of creation of Pollutant Release and Transfer Registers (PRTR) in Latin America[1].

Moreover, it is essential not only to collect information through stakeholder engagements but also to ensure consistent sharing of findings with stakeholders. This includes providing detailed information on the methodologies used for analyses and the results, with an emphasis on enhancing usability for a diverse range of actors. Although it was beyond the scope of this study, further research is needed to optimize the presentation and communication of these narratives, such as through visualizations like the systemic section. For the MRSC, beyond publishing these articles, the research will be condensed into a report, translated into Spanish, and disseminated to stakeholders involved in this study, including key actors with strategic planning roles.

[1] ECLAC. Observatory on Principle 10 in Latin America and the Caribbean. Accessed 15 sep 2024. Available at: [https://observatoriop10.cepal.org/en/maps/latin-america-and-caribbean-status-creation-pollutant-release-and-transfer-registers-prtr]

5.4. Conclusion

Sustainable management of nutrients is essential for the development of cities and regions, addressing two key urban challenges: food security and waste management. However, efforts towards nutrient circularity have often been fragmented or insufficiently coordinated across geographic areas, disciplines, landscapes, and political arenas. This lack of integration has impeded a comprehensive understanding of the systemic nature of nutrient management and, consequently, the development of holistic strategies.

On an international level, this research aims to bridge diverse global contexts and scientific disciplines, providing a versatile framework applicable to a variety of settings. On a local level, we hope that these findings will help connect actors across different disciplines, landscapes, political arenas, and sectors, fostering collaboration and integrated action.

Identifying the influencing factors for nutrient circularity was a crucial first step in this research, providing a comprehensive foundation that captures the diverse dimensions and disciplines involved in managing nutrient-containing flows. The nutrient circularity capacity assessment developed from this work offers a practical yet thorough tool for local actors and researchers. By utilizing existing data, this tool enables users to evaluate their city's potential to develop and implement nutrient circularity strategies and helps pinpoint priority areas that require further analysis. Our diagnostic framework introduces a strategic, multidimensional approach to assessing nutrient resource management from a territorial perspective, integrating principles and tools from urban metabolism and urban planning. Furthermore, our narrative development framework provides an innovative method for creating narratives that are grounded in robust scientific evidence while remaining adaptable to the interests and concerns of local stakeholders, all within a systemic nutrient circularity perspective.

In summary, the value of the frameworks presented in this work lies in the strategic integration of existing methods and principles from multiple disciplines. Rather than applying these techniques in isolation or without a defined practical purpose, they have been thoughtfully combined to address a specific and critical need: supporting city planners in enhancing the sustainable and circular management of nutrient-containing resources. We hope that this work encourages the development of integrated and effective strategies for managing nutrient-containing flows, whether in existing or future planning processes. Such strategies are crucial for the sustainability of cities and regions, contributing to the broader goal of sustainable urban development.

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Abstract:

Cities and metropolitan areas are essential to sustainable development, especially in managing nutrient flows such as fertilizers, food, and organic waste. However, integrating urban metabolism and nutrient circularity into planning remains challenging due to fragmented approaches. As cities grow and face climate change, the key question is: how can urban strategies better incorporate nutrient circularity? This research identifies and measures factors influencing nutrient flow management, proposing a three-step approach: identifying key factors, assessing them with a planning focus, and integrating findings into strategic planning. The focus is on South America, given its significant role in agrifood production and urbanization.

Article 1: This study develops a framework to measure Nutrient Circularity Capacity (NCC) in South American metropolitan areas (SAMAs), evaluating environmental, technical, economic, social, and political factors. It identifies 12 influencing factors across four themes—Material Flow, Food & Feed Value Chain, Knowledge Base, and Institutional Support—and links them to 11 indicators using multi-criteria analysis. Results show Montevideo, Uruguay, leading in NCC due to government support and innovation, while Paraguay and Bolivia rank lowest. The study emphasizes the need for localized strategies, with investments in innovation, waste management, and peri-urban agriculture as critical elements for improving nutrient circularity in the region.

Article 2: This research introduces a multidimensional diagnostic framework to enhance nutrient circularity in urban planning, bridging the gap between urban metabolism and practical planning. Applied to the Metropolitan Region of Santiago de Chile (MRSC), the framework assesses nitrogen (N), phosphorus (P), and potassium (K) flows across spatial, material, and social dimensions. Utilizing the UN's *Our City Plans* toolbox, data from local databases, literature, and 34 interviews helped map the agri-food-waste system. The findings reveal heavy reliance on imports for nutrients, significant losses from landfilled waste, and underutilized manure. Recovery rates for N, P, and K were 78%, 85%, and 52%, respectively, driven mainly by wastewater treatment. The diagnostic identified 45 key actors, highlighting the need for better collaboration across sectors. This framework supports planners in addressing nutrient flow challenges and enhancing collaboration between urban and rural sectors for improved circularity.

Article 3: This study presents a framework that integrates nutrient-flow diagnostics with stakeholder inputs and local strategies, constructing scenario narratives for circular urban development. Applied to Santiago, the framework connects the diagnostic phase with scenario building through three key tasks: contextualizing data, synthesizing findings, and creating narratives. Key challenges include limited waste treatment infrastructure, regulatory constraints, and collaboration barriers. Three narratives were developed to explore: increasing composting capacity for green urban areas, better utilization of animal residues in agriculture, and improving WWTP technologies for nutrient reuse. The framework bridges gaps in current urban plans and proposes strategies for enhanced nutrient circularity. By grounding decisions in stakeholder engagement and multidimensional analysis, it fosters systemic changes for sustainable urban development.

In conclusion, this research presents a comprehensive framework for advancing nutrient circularity in South America by systematically analyzing nutrient flows and enhancing strategic planning. It provides a structured, systemic approach to assessing key factors and translates findings into actionable insights for decision-makers and planners, helping cities and regions improve circular nutrient management practices.

Résumé :

Les villes et métropoles sont cruciales pour le développement durable, notamment dans la gestion des flux de nutriments tels que les engrais, les aliments et les déchets organiques. Cependant, intégrer la circularité des nutriments dans la planification urbaine demeure complexe en raison d'approches fragmentées. Face à l'expansion urbaine et au changement climatique, la question clé est : comment intégrer la circularité des nutriments dans les stratégies urbaines ? Cette recherche identifie et mesure les facteurs influençant la gestion des flux de nutriments, proposant une approche en trois étapes : identifier les facteurs clés, les évaluer dans une optique de planification et intégrer les résultats dans la stratégie urbaine. L'étude se concentre sur l'Amérique du Sud, un acteur majeur de la production agroalimentaire et de l'urbanisation.

Article 1 : Cette étude développe un cadre pour mesurer la Capacité de Circularité des Nutriments (NCC) dans les zones métropolitaines sud-américaines (SAMAs), en évaluant les facteurs environnementaux, techniques, économiques, sociaux et politiques. Elle identifie 12 facteurs d'influence répartis en quatre thèmes — Flux de Matériaux, Chaîne de Valeur Alimentaire, Base de Connaissances et Soutien Institutionnel — reliés à 11 indicateurs via une analyse multicritère. Les résultats montrent que Montevideo, en Uruguay, excelle en NCC grâce au soutien gouvernemental et à l'innovation, tandis que le Paraguay et la Bolivie se classent en bas. L'étude recommande des stratégies localisées, misant sur l'innovation, la gestion des déchets et l'agriculture périurbaine pour améliorer la circularité des nutriments.

Article 2 : Cette recherche propose un cadre diagnostique multidimensionnel pour renforcer la circularité des nutriments dans la planification urbaine, en comblant le fossé entre le métabolisme urbain et la planification pratique. Appliqué à la Région Métropolitaine de Santiago du Chili (MRSC), le cadre évalue les flux d'azote (N), phosphore (P) et potassium (K) à travers les dimensions spatiales, matérielles et sociales. Grâce à l'outil Our City Plans de l'ONU, les données locales, la littérature scientifique et 34 entretiens ont permis de cartographier le système agroalimentaire-déchets. Les résultats montrent une forte dépendance aux importations de nutriments et des pertes importantes liées aux déchets non traités et au fumier sous-utilisé. Les taux de récupération de N, P et K étaient de 78 %, 85 % et 52 %, principalement grâce au traitement des eaux usées. Le diagnostic identifie 45 acteurs clés, soulignant la nécessité d'une meilleure collaboration entre secteurs urbains et ruraux pour renforcer la circularité.

Article 3 : Cette étude propose un cadre intégrant le diagnostic des flux de nutriments avec les apports des parties prenantes et les stratégies locales pour élaborer des scénarios de développement urbain circulaire. Appliqué à Santiago, il relie le diagnostic à la construction de scénarios en trois étapes : contextualiser les données, synthétiser les résultats et créer des récits. Les principaux défis incluent des infrastructures de traitement des déchets insuffisantes, des contraintes réglementaires et des obstacles à la collaboration. Trois scénarios explorent l'augmentation du compostage, une meilleure utilisation des résidus animaux, et l'amélioration des technologies des stations d'épuration pour réutiliser les nutriments. Ce cadre propose des stratégies pour combler les lacunes des plans actuels et soutenir des transformations systémiques vers un développement urbain durable.

En conclusion, cette recherche propose un cadre structuré pour promouvoir la circularité des nutriments en Amérique du Sud. En analysant les flux de nutriments et en renforçant la planification stratégique, elle offre aux décideurs des recommandations pratiques pour améliorer la gestion circulaire des nutriments dans les villes et les régions.