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What agroecological perspectives in irrigated agriculture in the Mediterranean context to reconcile agricultural production and environmental sustainability? Application to drip irrigated market gardening in Central Tunisia

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Abstract

The principles of agroecology and those of irrigated agriculture are often considered to be contradictory, although science and innovation have made numerous efforts in technological improvements to limit the impact of irrigated agriculture on the environment. In particular, drip irrigation is often presented as a "green" solution because of its good theoretical performance. The development of drip irrigation has thus been promoted and encouraged by many public policies, particularly in the Southern Mediterranean. However, these optimistic efficiencies are often obtained in experimental conditions, and performances in real field conditions may substantially differ. The main challenges of this technology are the improvement of performances and its resulting food productivity while reducing its environmental impacts, in particular on water and nitrogen resources. Studies focusing on agroecology as a potential solution to overcome these issues are rare, especially in the arid and semi-arid irrigated areas of the Southern Mediterranean. The aim of this thesis is to analyze the agroecological performance of drip-fed market gardening in Central Tunisia (Merguellil plain). To this end, several complementary approaches are used, including surveys and observation of technical management routes (TMRs), their modelling using a crop model dedicated to fertigation scheduling (Optirrig model) and their assessment in both qualitative and quantitative manners. The study showed the existence of a wide diversity of TMRs within the panel of farmers studied. Although farmers do not design their technical management routes with an agroecological perspective, they often combine heterogeneous practices from this point of view, including environmentally virtuous practices. When the focus is on fertigation practices, the results show great potential for water and nitrogen savings combined with high yield gain potentials. Finally, the joint improvement of both irrigation management and cropping systems (through agroecological practices) would improve the performance of these market gardening systems, according to the environmental and economic components of sustainability. This thesis opens the way to broad prospects for improving the current performances of drip-irrigated agriculture, in order to combine environmental protection and agricultural production and initiate the agroecological transition of these systems.

Résumé étendu en français

Quelles perspectives agroécologiques en agriculture irriguée en contexte méditerranéen pour concilier production agricole et préservation de l'environnement ? Application au maraichage irrigué en goutte-à-goutte en Tunisie Centrale

Chapitre 1 : Introduction générale

L'irrigation est un facteur de sécurisation de la production agricole. Avec environ 20% des terres agricoles, l'agriculture irriguée représente près de 40% de la production alimentaire mondiale. Néanmoins, lorsqu'elle est conçue pour contribuer à une agriculture intensive, l'irrigation peut avoir des effets néfastes, à bien des égards. En effet, de par l'utilisation souvent accrue d'intrants chimiques et de produits phytosanitaires, l'agriculture irriguée contribue à la dégradation des écosystèmes et des ressources naturelles (notamment la surexploitation des ressources en eau). Dans la perspective de rendre l'agriculture irriguée plus durable, cette dernière doit faire face à trois défis sociétaux majeurs (qui peuvent constituer autant d'enjeux scientifiques) : améliorer la gouvernance des ressources en eau, réduire les impacts environnementaux tout en assurant une productivité agricole suffisante pour faire face à une demande alimentaire sans cesse croissante.

L'irrigation au goutte-à-goutte est souvent présentée comme une solution verte en raison de ses bonnes performances théoriques. En effet, le goutte-à-goutte est – théoriquement – l'une des techniques d'irrigation les plus efficientes, permettant de faire face aux enjeux agro-environnementaux majeurs en agriculture. Il permet à la fois de limiter les prélèvements en eau et de gérer finement les apports en fertilisants pour répondre aux besoins des cultures, et ce, dans un objectif d'assurer des rendements élevés et de limiter les externalités négatives. Cependant, les performances élevées du goutte-à-goutte, tant en termes d'efficience d'usage des ressources en eau que de productivité agricole, sont souvent obtenues dans des conditions expérimentales, tandis que ces mêmes performances dans les conditions réelles de terrain peuvent différer sensiblement.

Le goutte-à-goutte a été largement adopté par les agriculteurs, grâce aux économies d'eau pouvant être réalisées et à la simplification du pilotage de l'irrigation. Toutefois, tout processus d'adoption d'une nouvelle technologie engendre des adaptations des systèmes de culture et peut contribuer à l'émergence de systèmes agricoles nouveaux, comme cela a pu être observé en Inde (Kumar

and Palanisami, 2010). Le goutte-à-goutte pourrait-il alors concourir à l'émergence de pratiques alternatives telles que celles explorées par l'agroécologie ? Cet aspect a été peu exploré par la recherche scientifique, notamment dans les milieux arides et semi-arides du Sud de la Méditerranée, où cette technologie a été largement promue et encouragée par les politiques publiques, et où la transition des vers des systèmes agricoles plus durables – à l'instar du reste du monde – devient une nécessité.

Les principes de l'agroécologie et ceux de l'agriculture irriguée sont souvent considérés comme antagonistes bien que la science et l'innovation dans le domaine de l'irrigation aient fait beaucoup d'efforts en matière d'améliorations technologiques pour limiter l'impact de l'agriculture irriguée sur l'environnement. En effet, l'agriculture irriguée est souvent associée à une forte mobilisation des ressources naturelles et une dépendance en intrants exogènes. L'agroécologie quant à elle, fait référence à une écologisation des systèmes de production par la mobilisation des services écosystémiques pour limiter la dépendance vis-à-vis des intrants exogènes. Il existe plusieurs niveaux d'écologisation des systèmes comme le suggère le cadre conceptuel ESR (Efficience-Substitution-Redesign, Hill, 1998). Nous considérons dans cette thèse la technologie du goutte-à-goutte comme un potentiel vecteur de pratiques intéressantes pour initier les premières étapes de ce cadre (l'amélioration des efficiences voire la substitution des intrants chimiques). Ainsi, la thèse réexamine ce paradigme d'antagonisme entre agroécologie et irrigation et explore la possibilité de concilier les deux concepts, partant du postulat que le goutte-à-goutte pourrait être un levier d'action pour concevoir et implémenter une gestion plus agroécologique des cultures.

Ainsi, l'objectif général de la thèse est d'analyser dans quelles mesures les pratiques agroécologiques mises en place par les agriculteurs peuvent contribuer à améliorer les performances de l'irrigation au goutte-à-goutte. Cet objectif, appliqué à un site d'étude emblématique de l'agriculture irriguée semi-aride dans le sud de la Méditerranée - la plaine aval du Merguellil en Tunisie - se décline en trois sous-objectifs :

- la caractérisation fine des itinéraires techniques implémentés par les agriculteurs, par une méthode permettant d'en décrire la diversité, et leur degré d'intégration de pratiques agroécologies ;
- l'évaluation qualitative et quantitative des impacts environnementaux de ces itinéraires techniques, en termes d'usages de l'eau et de l'azote ;
- l'évaluation exploratoire des pistes d'amélioration des performances d'irrigation de ces mêmes itinéraires, par l'implémentation conjointe ou disjointe de pratiques agroécologiques locales et un meilleur pilotage de l'irrigation.

La plaine avale du Merguellil en Tunisie présente les conditions idéales pour réaliser ces investigations en contexte méditerranéen. En effet, les enjeux environnementaux rencontrés dans cette plaine sont à l'image de l'ensemble des périmètres irrigués de la région : fortes variabilités climatiques, prélèvements en eau croissants. L'étude est réalisée essentiellement à l'échelle de la parcelle et se focalise sur les processus incrémentaux (efficience, substitution) liés aux itinéraires techniques appliqués à une culture phare de l'agriculture irriguée de la région : le piment. Dans un premier temps, une description de ces itinéraires a été réalisée par une analyse typologique. Cela permet de comprendre les pratiques des agriculteurs et d'identifier celles en lien avec l'agroécologie. Ensuite, l'accent a été mis sur les stratégies de fertigation. Un suivi détaillé de celles-ci a été effectué sur le terrain et a permis de les évaluer sur la base de divers indicateurs, en utilisant Optirrig, un modèle de culture dédié au contexte de la fertigation. Enfin, des pistes d'amélioration de leurs performances ont été explorée par la modélisation de scénarii de pilotage de l'irrigation et de mise en œuvre de pratiques agroécologiques.

Chapitre 2 : Interroger l'agroécologie en milieux irrigués méditerranéens au travers de la caractérisation de la diversité des pratiques agricoles.

Dans les zones irriguées d'Afrique du Nord, l'agriculture est fortement basée sur l'utilisation d'intrants chimiques et une forte mobilisation des ressources en eau. En conséquence, l'on assiste en Tunisie à une surexploitation des nappes souterraines et une dégradation des terres agricoles. Dans ce contexte, la transition vers une agriculture plus durable passera d'abord par l'amélioration de l'efficience d'utilisation des ressources en eau, la substitution des intrants chimiques par des substituts organiques ou encore par des systèmes de culture alternatifs. Malgré des méthodes de production agricoles plutôt conventionnelles, de nombreuses pratiques compatibles avec l'agroécologie ont déjà été repérées dans les systèmes irrigués des plaines d'Afrique du Nord (Ameur et al., 2020). Bien que peu connues, et souvent noyées dans un large éventail de pratiques (Leauthaud et al., 2021), celles-ci pourraient servir de base pour concevoir de nouveaux systèmes agricoles plus respectueux de l'environnement. Dans ce chapitre, nous faisons l'hypothèse que de fortes contraintes et contrastes d'ordre social, économique et environnemental rencontrées dans les zones irriguées (Jamin et al., 2011) pourraient favoriser l'existence d'un large éventail de pratiques agricoles et de systèmes de production, à l'échelle des territoires irrigués des plaines du Maghreb. Des systèmes plus respectueux de l'environnement pourraient-ils se rencontrer au sein de cette diversité locale ? Dans quelle mesure ces pratiques sont-elles déjà présentes ou comment peuvent-elles être développées dans les

systèmes irrigués méditerranéens ? Pour répondre à ces questions, l'objectif de ce chapitre était de i) décrire la possible diversité des pratiques agricoles dans la zone d'étude et ii) d'identifier l'existence de pratiques respectueuses de l'environnement et les types d'agriculteurs qui les mettent en œuvre. L'étude se focalise sur l'analyse des itinéraires techniques appliqués à la culture du piment et des opérations culturales associées.

L'approche utilisée comporte quatre étapes successives. D'abord, une collecte de données par des enquêtes de terrain a été réalisée sur 45 parcelles. Des données ont été ainsi collectées sur les choix variétaux, la gestion de la fertilisation, les traitements phytosanitaires, l'irrigation, la gestion de la récolte. La deuxième étape a consisté en une série d'analyses statistiques combinant i) une analyse des composantes multiples, ii) une classification hiérarchique ascendante et iii) les règles d'association (Renaud-Gentié et al., 2014). Cette étape permet la construction et la description d'itinéraires techniques types. Les modalités de chaque opération culturale ont ensuite été classées qualitativement en fonction de leur impact potentiel sur les ressources naturelles, en se basant sur la littérature scientifique existante (Wezel et al., 2014; Ameur et al., 2020). Trois niveaux d'impact ont été qualifiés : les opérations culturales ayant un impact environnemental potentiellement positif (par exemple, pas d'application de pesticides), celles potentiellement nuisibles (par exemple, dose d'azote appliquée élevée) et celles n'ayant pas d'impact de premier ordre évident (par exemple, la date de transplantation). Un système de notation basé sur cette classification a permis d'évaluer les itinéraires techniques selon qu'ils sont potentiellement respectueux ou non de l'environnement. Enfin, dans la dernière étape, les données structurelles des exploitations ont été croisées avec les groupes d'itinéraires techniques formés, afin d'identifier les types d'exploitations mettant en œuvre chaque type de d'itinéraire.

L'étude a permis d'identifier, de manière générale, trois grands ensembles d'itinéraires techniques. Dans un premier lieu, l'on observe des itinéraires plutôt intensifs au regard des intrants chimiques, appliqués aux variétés hydrides de piment. Dans un second lieu, on distingue les itinéraires techniques appliqués aux variétés locales tunisiennes. Le dernier ensemble représente un mode de production assez particulier, consistant à produire le piment sur non pas un cycle comme dans le commun des cas, mais sur deux cycles culturaux. L'étude a en outre permis de construire sept sous-groupes (Figure 2.6, section 2.3.5). Au nombre de ceux-ci, on note des systèmes très intensifs en intrants chimiques azotés, mais modérés en traitement phytosanitaire. On a également des systèmes plus intensifs en traitements phytosanitaires, et plus modérés en intrants chimiques azotés. D'après l'évaluation qualitative effectuée, ces groupes pouraient être considérés comme étant peu respectueux de l'environnement. Ce

sont des itinéraires souvent mis en place par des agriculteurs ayant un accès indirect aux terres agricoles (locataires, métayers) et cherchant souvent à maximiser leur profit à court terme. Par ailleurs, des itinéraires techniques plutôt respectueux de l'environnement, privilégiant l'utilisation d'engrais organiques et parfois caractérisés par une absence totale de traitements phytosanitaires ont été également identifiés. Ceux-ci peuvent être observés chez les propriétaires terriens cherchant le plus souvent à préserver leur sol.

De manière générale, l'étude a montré l'existence d'une grande diversité d'itinéraires techniques appliqués à la culture du piment, au sein de ce petit territoire agricole. Ceux-ci n'étaient pas conçus dans une perspective agroécologique (optimisation des interactions écologiques dans un but productif), mais représentaient plutôt, pour la plupart, une combinaison de pratiques compatibles avec l'agroécologie (Wezel et al., 2014; Ameur et al., 2020) - telles que l'utilisation de fumier organique liquide, l'agroforesterie, ou encore l'association avec des légumineuses - et de pratiques beaucoup moins vertueuses. Parmi cette large gamme d'itinéraires techniques, certains étaient basés sur un usage beaucoup plus économe des produits chimiques. Des évaluations économiques, environnementales et agronomiques plus approfondies permettront de mieux appréhender leur pertinence. Le chapitre 3 décrit le suivi expérimental réalisé dans cette perspective.

Chapitre 3 : Suivi de parcelles

Ce chapitre présente le suivi réalisé en 2019 sur 11 parcelles de piment afin d'effectuer cette évaluation. Le suivi visait à estimer les variables pour lesquelles les données d'entretiens ne permettent qu'une première approximation, notamment les stratégies de fertigation et les rendements. L'analyse de ces données a permis d'établir pour chaque parcelle étudiée, les calendriers de fertigation et d'analyser la diversité des stratégies de fertigation et des rendements résultants des itinéraires techniques. Ces données sont mobilisées dans les chapitres 4 et 5 pour reproduire les pratiques par la modélisation, évaluer les performances et analyser des scénarii d'amélioration.

Des entretiens semi-directifs, des mesures *in-situ* et en laboratoire et des observations de terrain ont ont été réalisés sur chaque parcelle. Les données ont été ainsi collectées sur les itinéraires techniques : le pilotage de l'irrigation (dates, durée d'irrigation, débit de pompage), la fertilisation (dates, type d'engrais, doses appliquées), et les autres opérations (désherbage, traitements phytosanitaires, etc.); mais également la réponse de la culture (stades phénologiques, biomasse aérienne, indice foliaire, rendements), et les caractéristiques pédologiques.

Le suivi a montré que de manière générale, certains agriculteurs irriguent

de manière régulière, en ajustant la durée entre deux irrigations (environ 3 à 7 jours en moyenne) et les doses associées. D'autres en revanche, avaient une stratégie comprenant deux phases d'irrigation, séparées par une période d'arrêt d'irrigation relativement longue, pouvant atteindre trente jours. Durant la première phase d'irrigation, de faibles quantités d'eau sont apportées à la plante, à la transplantation et aux jours suivants. Dans la deuxième phase, comme dans le cas de la première stratégie, la durée entre deux irrigations et les doses sont ajustées par l'agriculteur, en fonction de la demande de la plante. Les agriculteurs estiment la demande en eau de la plante en fonction des conditions climatiques des jours précédents et d'un éventuel état de stress de celle-ci. La décision d'irriguer ou non relevait aussi d'un arbitrage entre différentes parcelles cultivées simultanément.

Par ailleurs, deux stratégies d'apport d'azote (par fertigation) ont également été observées. Dans une première stratégie, une quantité importante d'azote est appliquée à la transplantation (ou quelques jours plus tard), puis plusieurs fertigations sont fractionnées entre la floraison et les premières récoltes. Dans la seconde stratégie, les apports sont répartis dans le temps. Ces stratégies de fertigation ont pour effets, des consommations en eau très variables (260 et 2800 mm). Les doses d'azotes quant à elles dépendaient essentiellement du type d'engrais utilisé et variaient entre 50 et 180 kg d'azote par hectare. Par ailleurs, la diversité révélée par l'analyse typologique a été confirmée par le suivi détaillé des itinéraires techniques. Les rendements secs de piment était étaient aussi très variables : moins d'une tonne par hectare pour les plus faibles et environ 7 tonnes par hectare pour les plus élevés. Pour mieux expliquer cette variabilité, évaluer les impacts environnementaux des pratiques et proposer des pistes d'amélioration des pratiques et d'optimisation des rendements, les données collectées ont été placées dans un cadre conceptuel cohérent, porté par le modèle de culture Optirrig. Cette démarche avait pour but de :

- faciliter une inter-comparaison des parcelles ;
- estimer des variables difficiles à mesurer à la parcelle telles que le drainage et le lixiviation des nitrates ;
- projeter les gains possibles (en matière d'usage des ressources eau et azote et de rendements) par des changements du pilotage de la fertigation, pour éviter les gaspillages, la pollution.

Chapitre 4 : Modélisation et évaluation des impacts environnementaux des pratiques de fertigation en conditions réelles et peu jaugées : cas de la culture du piment à l'aide modèle Optirrig.

L'objectif de ce chapitre était d'évaluer les différentes pratiques de fertigation mises en œuvre par les agriculteurs et de proposer des pistes d'amélioration pour à la fois réduire la consommation en eau, les pertes en azote et accroître les rendements. Très peu d'études ont jusqu'ici porté sur l'évaluation en conditions réelles des stratégies de fertigation au goutte-à-goutte dans les régions du sud de la Méditerranée, avec pour but final de proposer des stratégies optimisées et adaptées aux logiques spécifiques des agriculteurs. La modélisation est une manière de simuler les principales composantes des bilans hydriques et azotés et leurs effets sur les rendements. Elle se prête donc bien à une telle analyse. Cependant, son utilisation dans un contexte de pratiques agricoles multiples et variées peut s'avérer particulièrement complexe. Il faut en effet être en mesure de simuler des conditions de sol hétérogènes et les différents itinéraires techniques. De plus, lorsque l'on effectue une analyse par la modélisation en conditions réelles où les données sont sujettes à des incertitudes, il est important de pourvoir intégrer celles-ci dans les analyses.

Pour atteindre l'objectif de ce chapitre, deux approches de modélisation, l'une déterministe (par essai-erreur) et l'autre, plus globale basée sur une méthode bayésienne de calibration groupe par groupe ont été testées. Après avoir sélectionné la méthode la plus adéquate, les stratégies de fertigation des agriculteurs ont été décrites. En se basant sur divers indicateurs agro-environnementaux, les implications de ces stratégies en termes d'impacts environnementaux (drainage et lixiviation des nitrates) et de productivité (rendement) ont été analysées. Enfin, des pistes d'amélioration de la gestion de la fertigation sont proposées, en comparant les stratégies des agriculteurs à une gestion optimisée de la fertigation générée par modélisation.

Les résultats ont montré qu'une approche déterministe de calibration par essai-erreur était moins appropriée dans notre cas d'étude à l'inverse de l'approche bayésienne de calibration. L'étude a en outre montré que les stratégies de fertilisation actuellement mises en œuvre par les agriculteurs pour la culture du piment génèrent un drainage massif d'eau (allant de 200 à plus de 2000mm) provoquant la lixiviation d'importantes quantités de nitrates (pouvant atteindre 220 kg d'azote par hectare). De plus, dans la majorité des des cas, les apportd d'eau aux plantes ne sont pas répartis de manière efficiente dans le temps, ce qui entraîne des stress hydrique et azoté fréquents.

Des économies d'eau et d'azote et conséquemment, des gains de rendement sont possibles dans la plupart des cas, en adoptant une stratégie d'irrigation optimisée (des quantités relativement faibles et des apports réguliers). Ainsi, dans leur ensemble, les pratiques étudiées peuvent être améliorées de manière substantielle.

Chapitre 5 : Vers une amélioration des systèmes maraîchers irriguées en goutte-à-goutte dans la plaine avale du Merguellil : quelles pratiques pour une meilleure durabilité ?

Pour aller au-delà de l'optimisation des stratégies de fertigation, ce chapitre analyse l'intérêt potentiel de l'intégration de deux pratiques agroécologique phares de la région (l'utilisation de fumier organique liquide et l'agroforesterie) dans les systèmes étudiés, pour améliorer l'efficience d'utilisation des ressources ou mieux valoriser celles-ci tout en augmentant la productivité et la rentabilité économique. L'objectif est de répondre à la question suivante : la mise en œuvre de pratiques agroécologiques localement répandues peut-elle améliorer les performances de l'irrigation, en ce qui concerne la productivité et l'efficience d'utilisation de l'eau et de l'azote ? Cette question a été traité en testant quatre scénarii de gestion (pratiques actuelles, calendrier d'irrigation optimisé, système combinant agroforesterie et utilisation de fumier liquide organique, système combinant agroforesterie et utilisation de fumier liquide organique avec une irrigation optimisée). Chaque scénario est analysé par rapport aux dimensions agro-environnementale et socio-économique, représentées par les bilans de l'eau et de l'azote (apports, drainage et lessivage des nitrates), le rendement total et les données économiques (coûts de l'eau, des engrais énergétiques et de la main-d'œuvre, produit brut et charge de travail). L'effet de chaque scénario sur chacune de ces variables a été estimé en se basant sur les mesures et observations réalisées sur le terrain, les simulations effectuées dans le chapitre précédent et des hypothèses issues d'expérimentations identifiées dans la littérature. L'analyse a montré que des marges d'amélioration existent, pour la plupart des parcelles étudiées. Les scénarii alternatifs testés peuvent en effet réduire les impacts environnementaux pour certains agriculteurs (prélèvements en eau, drainage, lixiviation des nitrates) mais avec un coût économique qui se traduirait par une baisse de la rentabilité. Pour d'autres, migrer vers un système combinant agroforesterie, utilisation de fumier liquide organique et une irrigation optimisée devrait permettre de limiter les impacts environnementaux tout en améliorant la productivité et la rentabilité économique des cultures. Toutefois, ces scénarii pourraient générer une augmentation non négligeable de la charge de travail, dans la plupart des cas. Par ailleurs, ces pistes d'amélioration varient d'une parcelle à une autre. Il y a donc nécessité d'analyser les situations au cas par cas. Toutefois, l'amélioration de l'usage des ressources et des rendements à l'échelle territoriale par exemple, devrait passer avant tout par une meilleure gestion de l'irrigation, puis pour des systèmes gérant mieux leurs intrants (eau et azote), par la mise en place de pratiques agroécologiques.

Les analyses présentées dans ce chapitre sont exploratoires. Les amélirations de rendement et de revenus sont hypothétiques. Néanmoins, sur la base d'hypothèses simples mais réalistes, ce chapitre montre que la mise en place pratiques agroécologiques combinée avec un meilleur pilotage de l'irrigation pourrait être une piste intéressante pour améliorer la durabilité des systèmes maraîchers irrigués au goutte-à-goutte dans la plaine avale du Merguellil. De tels scénarii, visant une amélioration conjointe de l'usage des ressources eau et azote, permettraient une meilleure rentabilité économique de la culture. Ces résultats restent à être confirmés, par une analyse à l'échelle des systèmes de production des impacts que la mise en place de ces pratiques pourrait générer, notamment en termes d'organisation du travail.

Chapitre 6 : Discussion générale

Nos travaux de recherche, menés dans une plaine agricole du sud méditerranéen dominée par les cultures irriguées à forte valeur ajoutée, posent tout d'abord le constat que les systèmes étudiés n'ont pas été conçus dans une perspective agroécologique. Au contraire, c'est souvent la maximisation du profit par une augmentation des rendements, poussée par une intensification chimique des systèmes, qui domine comme modèle de production agricole. Nous montrons cependant qu'au sein de ces systèmes de cultures, un certain nombre de pratiques compatibles avec l'agroécologie sont largement utilisées. Certaines de ces pratiques, tels que les associations de culture ou la fertilisation organique, pourraient être des pistes intéressantes pour une meilleure gestion des ressources. Il convient cependant d'analyser leur intérêt en prenant en compte à la fois l'ensemble des opérations culturales mise en place et les logiques des agriculteurs. Cette thèse montre que ces pratiques dites agroécologiques sont pour la plupart intégrées au sein d'itinéraires techniques moins vertueux en termes d'usages des ressources. En apportant un regard et une analyse spécifique sur les stratégies de fertigation, nous montrons qu'il existe d'importantes marges d'amélioration des performances des pratiques de fertigation, pour limiter les pertes en eau et azote et augmenter les rendements. Au regard de la surutilisation drastique des ressources observée, la mise en place de pratiques agroécologiques ayant un impact sur les cycles de l'eau et de l'azote, ne peut à elle seule, constituer une voie d'amélioration des performances de ces systèmes. Ce constat va à l'encontre de la plupart des analyses qui évaluent – souvent en conditions expérimentales – l'intérêt des pratiques agroécologiques, en mettant en avant les meilleures efficiences associées à celles-ci. Nonobstant, ces pratiques pourraient avoir d'autres vertus, en affectant plutôt les composantes socio-économiques du système. Ainsi, sur notre cas d'étude, nous montrons que

c'est l'amélioration conjointe à la fois du pilotage de l'irrigation et des systèmes de cultures qui permettrait d'améliorer les performances, selon les deux composantes environnementales et économiques de la durabilité. La composante sociale a été moins étudiée. Nous pouvons cependant formuler l'hypothèse que les améliorations obtenues par notre analyse exploratoire, affecteraient l'organisation du travail. Ceci pourrait être une contrainte principale à considérer. Cette thèse met également en évidence l'existence, au sein du territoire étudié, d'itinéraires techniques qualifiés de plus « vertueuses ». D'après les mesures réalisées, certaines parcelles présentent à la fois des rendements élevés et un usage en intrants chimiques modéré. Ces modes de production que mettent en place un nombre limité d'agriculteurs, sont des exemples intéressants de systèmes de production plus durables, et peuvent servir de modèle d'étude.

En se référant au cadre conceptuel de l'ESR, la thèse apporte un ensemble de connaissances concernant la première étape (Efficience) et dans une certaine mesure la seconde (Substitution) dans le contexte de la plaine aval du Merguellil, en Tunisie centrale. Elle met en lumière le large potentiel d'amélioration des efficiences au sein de ces systèmes irrigués, à travers les quantités excessives d'eau et de nutriments utilisés et les possibilités de gain de rendement. Les résultats confirment que la bonne performance de l'irrigation au goutte-à-goutte est associée avant tout à une nécessaire appropriation de la technologie. On peut ainsi remettre en question la position de certains auteurs tels que Wezel (2017), qui présentent l'irrigation au goutte-à-goutte comme une pratique agroécologique d'économie d'eau pour atteindre les performances recherchées par l'agroécologie. En effet, l'irrigation au goutte-à-goutte doit plutôt être considérée comme le vecteur d'autres pratiques respectueuses de l'environnement, et peut permettre d'atteindre les performances recherchées par l'agroécologie si elle est gérée de manière efficiente.

Par ailleurs, sur le plan méthodologique, la thèse traite de l'un des principaux défis de la recherche en sciences de l'irrigation : la pluridisciplinarité. Les résultats sont issus d'un ensemble de cadres d'analyse complémentaires provenant de différentes disciplines, de la typologie (agronomie des pratiques) à l'évaluation qualitative des impacts environnementaux (écologie), en passant par le suivi et la modélisation sur le terrain en conditions paysannes (agronomie, agro-hydrologie). L'originalité de la thèse réside dans cette complémentarité des cadres d'analyse et dans l'utilisation de méthodes de collecte de données différentes, allant des enquêtes aux mesures et observations terrain ou encore la simulation numérique. L'analyse typologique a été entreprise afin de rester en accord avec l'un des principes fondamentaux de l'agroécologie suggérant une compréhension des pratiques et conditions agricoles locales avant de proposer des solutions d'adaptation. Notre approche centrée sur le milieu réel et

l'agriculteur, visait à mettre celui-ci au centre des analyses, ce qui a permis de mettre en lumière (localement) des performances mitigées du goutte-à-goutte, jusqu'ici masquées des performances théoriques associées à cette technologie.

D'un point de vue méthodologique, nos travaux représentent une approche innovante d'analyse des pratiques agricoles et d'évaluation agroécologique. Au travers d'un ensemble de cadres conceptuels complémentaires (typologie réalisée à partir d'une analyse rigoureuse de l'itinéraire technique ; méthodes pour utiliser une approche de modélisation en conditions réelles et peu jaugées), la méthodologie utilisée dans cette thèse permet d'analyser et d'évaluer pratiques agricoles dans leur diversité, en tenant compte des incertitudes de données, et en mettant l'agriculteur au centre des analyses.

En termes de perspectives de recherche, les niveaux 2 (substitution) et 3 (Redesign) du cadre conceptuel de l'ESR devraient être étudiés plus en profondeur. En effet, bien que la thèse ait analysé l'intérêt de la substitution des engrais chimiques par le fumier liquide et le passage à des systèmes agroforestiers (deux pratiques qui se réfèrent à ces deux niveaux du cadre ESR), les hypothèses faites étaient parcimonieuses et les conclusions exploratoires. Par ailleurs, l'évolution des systèmes irrigués peut s'enliser dans des états non durables si les changements mis en œuvre sont uniquement incrémentaux ("Augmentation des efficiences" ou "Substitution"). Il est donc nécessaire d'expérimenter des systèmes plus transformatifs et d'aller vers la co-conception de systèmes de culture adaptés. Cette co-conception est d'ailleurs l'une des limites de la thèse car notre approche méthodologique, bien que centrée sur l'agriculteur, n'a pas été mise en œuvre de manière participative. Les solutions que nous proposons nécessitent ainsi une validation, par exemple au travers d'ateliers participatifs impliquant les agriculteurs et les acteurs locaux. Enfin, il serait pertinent d'explorer, dans la continuité de la présente thèse, d'autres dimensions de l'agroécologie au sein des systèmes étudiés, notamment la santé du sol.

Contents

Acknowledgements **v**

Abstract **ix**

Résumé étendu en français **xi**

1 General introduction **1**
1.1 Irrigated agriculture 1
1.1.1 Irrigation and agriculture today 1
1.1.2 Science frontiers for irrigated agriculture 3
1.2 Drip irrigation: a technology to improve performance of irrigated agriculture 5
1.2.1 Drip irrigation systems: principle, advantages and limits . 5
1.2.2 Assessment and improvement of drip irrigation systems: what prospects? 7
1.2.3 Agroecology and irrigated agriculture 8
1.3 Problems and objectives 12
1.4 Case-study 13
1.4.1 Irrigation in Southern Mediterranean 14
1.4.2 Irrigated agriculture in Tunisia 14
1.4.3 Agroecology in Tunisia state of the art 17
1.4.4 The Merguellil downstream plain 18
1.5 General methodology 20
1.6 Manuscript layout 21

2 Challenging agroecology through the characterization of farming practices' diversity in Mediterranean irrigated areas **25**
2.1 Introduction 26
2.2 Materials and methods 28
2.2.1 Study site 28
2.2.2 Methodological approach 29
2.2.3 Sampling and data collection 31

2.2.4 Database and variables construction . . . 31
2.2.5 Qualitative assessment of the potential environmental impact of farming practices . . . 32
2.2.6 Statistical analysis using the "Typ-iti" method . . . 32
2.2.7 Identifying farm types associated to each cluster . . . 34
2.3 Results . . . 35
2.3.1 Technical operations used for statistical analysis . . . 35
2.3.2 MCA and clustering . . . 35
2.3.3 Association rules and cluster . . . 39
2.3.4 Description of the seven clusters of TMRs . . . 39
2.3.5 Identifying farm types associated to each TMR . . . 42
2.3.6 Discussion . . . 45
2.4 Conclusion . . . 49

3 Field monitoring **51**
3.1 Introduction . . . 52
3.2 Methodology . . . 53
3.2.1 Plot sampling . . . 53
3.2.2 Experimental design: field and TMR characteristics . . . 55
3.2.3 The monitoring of TMRs . . . 56
3.2.4 Monitoring of fertigation . . . 56
3.2.5 Crop data: yield, biomass, LAI and root depth . . . 59
3.2.6 Soil data . . . 63
3.2.7 Data analysis, uncertainty and error propagation . . . 64
3.3 Results: analysis of fertigation strategies and diversity of aboveground biomass and yields . . . 66
3.3.1 The cropping calendars . . . 66
3.3.2 Duration of irrigation and irrigation schedules . . . 66
3.3.3 Fertigation strategies . . . 68
3.3.4 Above ground biomass and yield . . . 71
3.3.5 Crop management data and yield diversity . . . 73
3.4 Discussion . . . 73

4 Modelling and assessing environmental impacts of fertigation practices under field conditions: a case-study of chili-pepper using the Optirrig model. **77**
4.1 Introduction . . . 78
4.2 Materials and methods . . . 79
4.2.1 Study sites and data acquisition . . . 79
4.2.2 Methodology . . . 83
4.2.3 The Optirrig model . . . 84

4.2.4 Model calibration . . . 85
4.2.5 Reference-case simulation and performance indicators . . 89
4.2.6 Alternative scenarios and optimization . . . 89
4.3 Results . . . 91
4.3.1 Model calibration: approach A1 (trial-and-error) . . . 91
4.3.2 Approach A2: Numerical Analysis . . . 91
4.3.3 Merits and drawbacks of both approaches . . . 95
4.3.4 Reference case simulation and analysis . . . 96
4.3.4.1 Modelling farmers' practices: water and nitrogen budgets . . . 96
4.3.4.2 Modelling farmers' practices: water and nitrogen stresses . . . 97
4.3.5 Alternative scenarios and optimization . . . 98
4.3.5.1 Optimized practices and expected gains . . . 98
4.3.5.2 Description of the optimized scenario . . . 100
4.4 Discussion and conclusion . . . 100

5 Towards an improvement of drip irrigated market gardening systems through agroecological practices 103
5.1 Introduction . . . 103
5.2 Practices to improve the performances of the studied systems . . 104
5.2.1 Manure tea . . . 106
5.2.2 Agroforestry . . . 106
5.2.3 Irrigation management . . . 108
5.3 Scenario hypotheses and assumptions . . . 108
5.3.1 Scenarios . . . 108
5.3.2 Water and nitrogen budgets . . . 109
5.3.3 Yield components . . . 110
5.3.4 Gross revenue and other socio-economic variables . . . 111
5.4 Results . . . 112
5.4.1 Water and nitrogen budgets . . . 113
5.4.2 Yield components . . . 113
5.4.3 Socio-economic impacts . . . 116
5.5 Discussion and conclusion . . . 116

6 General discussion and conclusion 119
6.1 Summary of results . . . 119
6.1.1 Contribution of the thesis . . . 123
6.1.2 Contribution to knowledge . . . 123
6.1.3 Methodological contribution . . . 125
6.2 Limits of the study . . . 127

6.2.1 The scale of analysis and studied systems 127
6.2.2 A farmer and field-focused analysis 128
6.2.3 Comparison of systems and criteria used 129
6.2.4 Two-year complementary analyses 129
6.3 Perspectives 130
6.3.1 Agroecological perspectives in the Southern Mediterranean irrigated systems 130
6.3.2 Towards a territorial evaluation of irrigated market gardening crops 131
6.3.3 Socio-economic factors influencing management logics . . 132
6.4 General conclusion 132

A Experimental conditions **155**

B Additional figure of statistical analyses (Chapter 2) **157**

C Scenarios and related agro-environmental variable and socioeconomic variables (Chapter 5) **159**

D Marketable yield per plot and harvest **161**

E Conference abstracts **169**

F Thesis defense **175**

G Additional pictures **177**

List of Figures

1.1 Some examples of irrigated systems (a) shallow system in Tillabéri, Niger (© Florence Deram Malerbe); (b) mountain irrigation in Southern Vietnam (© Jean-Yves Jamin); (c) irrigated plain in Central Tunisia (© Olivier Grunberger) 2
1.2 Global Map of Irrigation Areas equipped for irrigation around the year 2000 as percentage total area. Source: Siebert et al. (2005) . . 3
1.3 Layout of a drip irrigation system (Source: USDA (1997) 6
1.4 Historical evolution of Agroecology (adapted from HLPE (2019)). The dimension and elements focused on in this thesis are colored in green. 9
1.5 The 10 elements of agroecology from FAO (2018) and the 5 levels of agroecological transition (Hill, 1998; Gliessman, 2016) 10
1.6 Map of Tunisia showing the the climatic zones (from Hamdane (2019)) 16
1.7 Traditional water harvesting in agroecosystems of Tunisia (Altieri and Toledo, 2005) 17
1.8 The Merguellil downstream plain 19
1.9 The Merguellil downstream plain landscape (Photo: O. Grunberger) 19
1.10 Studied system boundaries. 20
1.11 Framework for performance assessment of irrigation adapted from Bos et al. (2004), applied to each specific objective. 22

2.1 (a) Location of the case-study site: the Merguellil downstream plain in Central Tunisia; (b) interviewed farms (black dots). 30
2.2 Methodological approach. 30
2.3 MCA Plot of individuals and variables (TOs) modalities 38
2.4 MCA Plot of individuals and variables (TOs) modalities 40
2.5 Number of rules for each cluster and maximum length of rules in clusters. 41

2.6 Description of TMRs. (a) TOs linked to each cluster according to the three MCA, AHC and data-mining steps. (b) Schematic representation of the same results, hightling the potentially agroecological TOs according to literature 43

3.1 Examples of fertilizer application methods in the Merguellil downstream plain: (a) injection of fertilizer into the drip irrigation system, (b) application of Diammonium Phosphate, (c) injection of Ammonium Nitrate into the main irrigation pipe. 51
3.2 Field data collection methodological flowchart. 54
3.3 The study zone with the location of the monitored fields. 55
3.4 Thermochron iButton fixed on irrigation and empty pipes. 59
3.5 Flowmeter probes installed on an irrigation pipe. 60
3.6 (a) chili-pepper plot before harvesting, (b) marketable yield measurement using 25 m^2 plots, (c) marketable yield measurement through the number of crates harvested, (d) weighting of total harvest 61
3.7 Root development of chili-pepper, 73 days after transplanting. . . 62
3.8 Leaf Area Index measurement (a) scanned image; (b) processed image using the ImageJ software. The graduated marker are used to set the scale of the image 62
3.9 Field capacity and welting point measurement (a) sample saturation, (b) preparation for pressurizing 63
3.10 Variables calculation and uncertainty estimation. The green rows represent model input variables (intermediary variables in light green; blue rows are model outputs (with intermediary variables in sky blue 65
3.11 Cropping calendar for each field, presenting the decade of soil preparation and transplantation, the key periods of fertilization, irrigation and harvest. 67
3.12 Example of temperature time series recorded one field. The black line is the irrigation pipe temperature and the doted line is the air temperature. The records show temperature plateau occurring when water flows into the irrigation pipe. The detected irrigation phases are overlaid in grey. 68
3.13 Example of temperature time series recorded where the detection of irrigation phase was trickier. The black line is the irrigation pipe temperature and the dotted line is the air temperature. The irrigation phases are overlaid in green was not detected but confirmed by the farmer. 68

3.14 Example of temperature time series recorded with missing data for air temperature and showing "fake" plateaus (overlaid in blue). The black line is the irrigation pipe temperature. The missing records were replaced by the average temperature of the irrigation pipe on all the monitored plots in red doted line. The irrigation phases overlaid in grey were detected but required the confirmation of the farmer. 69
3.15 Total amount of irrigation water and nitrogen supply, for all monitored plots, for one cropping season. 70
3.16 Cumulative amounts of irrigation water (blue lines), and nitrogen application (red bars), for all monitored fields, for one cropping season. 71
3.17 Observed dry biomass (a), marketable yield (b) and dry yiel (c) per plot (scatter plot) and dispersion (boxplot next to the scatter plot). The error bars represent the uncertainty related to each value. The dry yield was obtained by deducting the water content from the marketable yield: 91% for hybrid variety and 84% for local variety. 72
3.18 Observed yields and relevant management data: (a) number of days from planting to last harvest, (b) planting density, (c) N fertilizer applied, (d) total irrigation applied 74

4.1 The Merguellil downstream plain (a) and location of the monitored plots and weather stations (b) with illustration of fertigation practices, as injection of fertilizers into the drip irrigation system (c) and injection of ammonium nitrate into the main irrigation pipe (d). 80
4.2 Framework of the study, with successive steps of semi-automated model calibration (sketch 1), reference-case simulation and analysis (sketch 2) and tentative optimization of farmers' practices through the formulation of alternative scenarios (sketch 3). 83
4.3 The structure and principle of the Optirrig model (from Chevironet al., 2016, 2020) showing the link between model variables (a) and a focus on the simplified nitrogen cycle used (b). Both schemes connect through the nitrogen stress SN calculated in (b) and called in (a). 85
4.4 LAI - Leaf Area Index curve (a) and TDM – Total aboveground Dry Biomass curve (b) obtained on plot P6 from the Trial-and-error calibration of Approach A1 92

4.5 Results of the sensitivity analysis performed with the Morris method on the Optirrig model, targeting six variables of interest: final crop yield (a), final aboveground biomass (b), cumulative drainage (c), cumulative actual evapotranspiration (d), cumulative nitrate leaching (e) and cumulative plant nitrogen uptake (f). 93
4.6 LAI (a, b, c) and TDM (d, e, f) curves for the accepted ("behavioral") parameters sets (in grey) on plots P1 (a, d), P6 (b, e) and P9 (c, f). The black line represents an example of one parameter set . 94
4.7 Observed and simulated yields: (a) approach 1 and (b) approach 2. The black oblique line represents the 1:1 axis. Vertical bars represent simulations error while horizontal bars represent measurement error. 95
4.8 simulated water drainage and nitrate leaching for each field. . . . 96
4.9 Water and nitrogen stress occurrences throughout the cropping cycle: red bands represent nitrogen stress, blue bands represent water stress, with their resulting intersection on purple, grey bands represent crop growth period. 97
4.10 Potential yield gains and economy in the use of both water and nitrogen resources by plot, resulting from model optimization of fertigation strategies. 99
4.11 Indicators of productivity and resource use efficiency. Indicators with “opt” represent value computed for the optimized strategy. WP: Water Productivity; WAE: Water application efficiency; NUE: Nitrogen Use Efficiency; WS: Water saving; NS: Nitrogen saving; YG: Yield gain. 99

5.1 Some agroecology-compatible practices in Tunisia (Ameur et al., 2020): (a) liquid manure production basin; (b) pepper-olive grove agroforestry system 105
5.2 Olive tree chili-pepper agroforestry system monitoring experimental set up, 2019. (Credit: K. Akakpo, 2019) 107
5.3 Olive trees and annual crop roots zones exploration. The pit was realized at the center of olive trees inter-row (Credit: K. Akakpo, 2019). 107
5.4 Agro-environmental variable and socio-economic variables (P1 to P6) 114
5.5 Agro-environmental variable and socio-economic variables (P1 to P6) 115

6.1 Synthesis of the thesis: implementation of the Bos et al. (2004)’s conceptual framework to each specific objective. 121

6.2 Synthesis of results and key variables and indicators describing TMRs. 123

A.1 Meteorological data measured at a local weather station (a) rainfall (b) average daily temperature; (c) solar radiation; (d) air relative humidity; (e) average wind speed. The line represent data measured in 2019. The grey band represents the 10 years daily average 155

B.1 Cluster tree obtained after HAC 157

C.1 Scenarios and related agro-environmental variable and socioeconomic variables 160

F.1 Thesis defense permanent link `https://www.youtube.com/watch?v=0k5aQKMdXdM` 175

List of Tables

2.1 Criteria used to classify TOs as "harmful" or agroecology-compatible or not). Each TO is categorized according to the ESR conceptual framework. E= Efficiency increase; S = Substitution; R = Redesign 33
2.2 Technical operations (TO), and their defined modalities, used for the MCA and next steps of the study. Each TO has two to four modalities. NOFA = No Organic Fertilizer Application, SAP = Soil Application before Planting, SAPF = Soil Application before Planting and Fertigation, SAPP= Soil Application before Ploughing and Planting. Early planting = before April; in-season planting = from April to May; off-season planting = from June to August. * less than 15 days after planting; ** more than 15 days after planting. NA: No answer 36
2.3 Cluster description. Modalities very significantly and significantly linked to the cluster are set in bold and italic, respectively. NOFA = No Organic Fertilizer Application, SAP = Soil Application before Planting, SAPF = Soil Application before Planting and Fertigation. Total rating: < 2: low; [2, 6[: neutral; [6, 10[: moderate; > 10: high. 37
2.4 Plots and characteristics of farms: for each cluster, percentage of plots located in farms having each criterion. UAA: useful agricultural area. 44

3.1 Main characteristics of the topsoil layer (0–20 cm) on each plot . . 57
3.2 Main characteristics of the topsoil layer (0–20 cm) on each plot . . 57
3.3 Description of the irrigation systems 58

4.1 Set of indicators describing irrigation strategies, in terms of doses and scheduling, implemented on each field. Irrigation dose indicators: AID, MAIA, MIIA are average, maximum and minimum irrigation dose, and TIA the total irrigation amount. Irrigation scheduling indicators: LDP is the longest dry period in the 120 first days after transplantation, ADI the average number of days between two irrigations and TNI the total number of irrigations . 81
4.2 : Soil properties and management data on each plot, FC is field capacity (measured at 3 bars), WP is wilting point (measured at 15 bars), CD is cycle duration and Σ N the cumulative nitrogen amounts 82
4.3 Reference values for the tested model parameters.* Value specific to local variety 88
4.4 : Indicators of productivity, efficiency and gains from optimization. "Opt" stands for "Optimized" 90
4.5 Set of indicators to compare current fertigation strategies and the proposed optimized strategies: LDP: longest dry period in the 120 first days after transplantation, AIA= average irrigation amount, MIA = Maximum irrigation amount, MiIA = minimum irrigation amount, TIA = total irrigation amount, AIF = Average irrigation frequency, TNI = total number of irrigations; NDWS = number of days of water stress, NDNS = number of days of nitrogen stress. Bold: optimized strategy, non-bold: current farmer's strategy . . 100

5.1 Methods used to estimate each variable for all scenarios. 111

6.1 Research questions and objectives 120

Chapter 1

General introduction

1.1 Irrigated agriculture

1.1.1 Irrigation and agriculture today

Irrigation is instrumental for global agriculture. It has enabled the expansion of cultivated lands over the last decades. It secures water availability for crops and thus allows substantial yield increases. After World War II, most developed countries invested on modernized large-scale irrigation projects (such as the Columbia Basin Project in the United-States), to support food production and increase crop productivity. In developing countries, numerous ambitious irrigation projects were realized at the same period, such as the office of Niger, the irrigated perimeters of Gharb or Saiss in Morocco, the Mitidja plain in Algeria, the Medjerda plain in Tunisia, etc. with a diversity of irrigated systems (Figure 1.1).

Nowadays, approximately 75% of the irrigated lands are located in developing countries, a large part concentrated in North Africa and the Near and Far East (Schoengold and Zilberman, 2004; Siebert et al., 2005) with up to 100% of lands irrigated in some locations in the 2000s as shown on Figure 1.2. More specifically, in the early 80s, the Northern African countries implemented policies of modernization of irrigated systems (Bouarfa et al., 2020).

According to the FAO (2017), irrigation water accounts for about 70% of total withdrawals. It is a necessity for viable agriculture production in certain areas or can significantly improve already viable productions (Leenhardt et al., 2020). In semi-arid areas, this mobilization of additional water resources is instrumental to increase crop production. Due to these assets, irrigated agriculture contributes to meeting the ever-increasing food demand caused by the rapid growth of the world's population, by substantially contributing to global food production. Indeed, occupying approximately 20% of agricultural lands, it accounts for about 40% of global food production (FAO, 2015). Irrigation is



Figure 1.1: Some examples of irrigated systems (a) shallow system in Tillabéri, Niger (© Florence Deram Malerbe); (b) mountain irrigation in Southern Vietnam (© Jean-Yves Jamin); (c) irrigated plain in Central Tunisia (© Olivier Grunberger)

an essential component of the water cycle in addressing water security (Sustainable Development Goal (SDG) 6), sustainable consumption and production (SDG 13), food insecurity (SDG 2) and poverty (SDG 1) goals. On another plan, irrigated agriculture can constitute – because of its environmental impacts – an obstacle for the preservation of biodiversity (SDG 15) and the sustainability of many ecosystems. These costs are not only at the agroecosystem scale (through drastic modifications of landscapes and landcover), but also potentially downstream, through water withdrawals, the modification of natural habitats such as wetlands, or water pollution (Perret and Payen, 2020). Indeed, irrigation can be conceptualized as *"the process by which [...] land and water (considered as a collective resource) are mobilized to grow crops for home consumption and markets, while generating positive and negative socio-economic and environmental externalities"* (Sanchis-Ibor and Molle, 2019). So, despite all of its benefits, development of irrigation

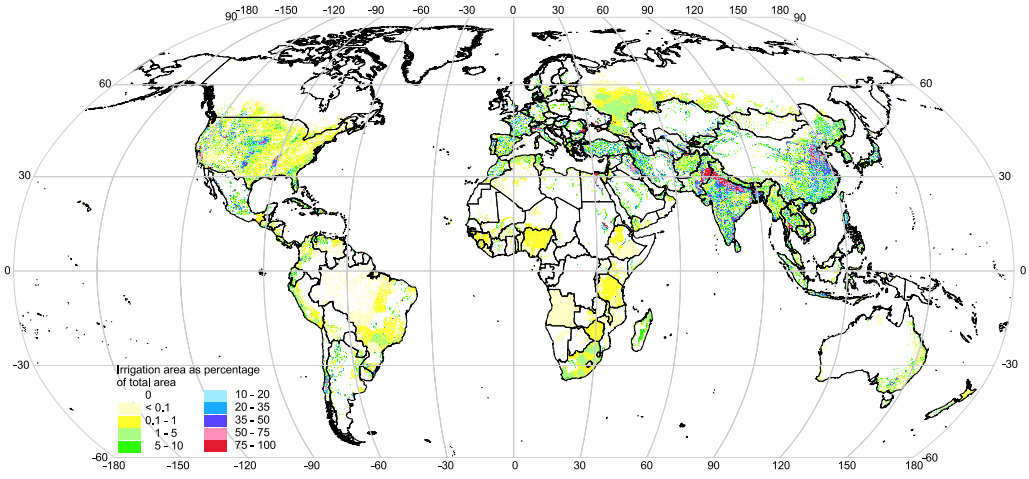


Figure 1.2: Global Map of Irrigation Areas equipped for irrigation around the year 2000 as percentage total area. Source: Siebert et al. (2005)

has substantial costs. What are the trade-offs for both substantial food production and ecosystem conservation? The following sections present a literature review on the challenges related to irrigation science.

1.1.2 Science frontiers for irrigated agriculture

Irrigation sciences combine the worlds of agriculture, water management, technology and research; major activities that cut across intricate social, economic, environmental, and political realities (Sanchis-Ibor and Molle, 2019). To result in sustainable irrigation, three main science frontiers can be assigned to irrigated agriculture: governance of water resources (rather related to socio-economic stakes); the need to jointly improve irrigation and production performances in a context of climate change, and finally, the reduction of the environmental impacts of irrigation.

As a collective resource, there are often governance issues concerning agricultural water use: who controls the resource and how is water distributed? According to OECD (2015), *water governance is the set of rules, practices, and processes through which decisions for the management of water resources and services are taken and implemented, and for which decision-makers are held accountable*. The stakes related to water governance are complex. The fundamental challenge is to establish rules and management policies that take account of and are adapted to the variable and continuously changing societal, economic and environmental conditions (Batchelor, 2007).

Concerning irrigation performances and related crop productivity, there has been substantial improvements in the last decades through modernization of irrigation infrastructure at both the irrigation scheme, farm and plot levels, in part due to technological developments. However, the irrigation performance

gap still remains substantial. For instance, losses (e.g. channel infiltration) in collective networks can still be important. At the crop scale, it has been shown that the fraction of irrigation water delivered and used for crop transpiration was low (less than 50% in general) (Batchelor et al., 1996). This share of water not valuated by crops depends on the irrigation system and includes direct evaporation and wind drift, interception and storage by the crop canopy, run-off and drainage (related to excessive or non-uniform application), soil evaporation, weed transpiration and residual soil water after harvest (Hsiao et al., 2007; Serra-Wittling et al., 2019). Given this wide diversity of causes, improving irrigation efficiency is a daunting challenge (Hsiao et al., 2007).

Furthermore, irrigated agriculture is a source of pollution. With the use of fertilizers and pesticides, drainage and run-off generate pollutant transfer (e.g. nitrate leaching), leading to water resources and ecosystems degradation. In addition, the implementation of irrigation practices has been taking place for several decades in a particular context of climate change where water availability is increasingly limited while food demand continues to grow.

As illustrated here, both societal and scientific stakes related to irrigation are multiple and take place at different temporal and spatial scales. They are addressed by and involve diverse stakeholders including scientists, policy makers, farmers, environmentalists, etc., and all deserve to be handled. This thesis focuses on the scientific aspect of the agronomic and environmental challenges of irrigation, which are further developed hereafter.

A first step of action to improve the efficiency of the irrigated systems is to assess their performance and then, take action to reach higher performances. Performance assessment of irrigation can be defined as *"the systematic observation, documentation and interpretation of activities related to irrigated agriculture with the objective of achieving an efficient and effective use of resources by providing relevant feedback to the scheme management at all levels"* (Bos et al., 2004). Many studies and research projects have focused on improving the performance of irrigation systems. Scientists agree to say that substantial water savings can be achieved through the proper design and management of irrigation systems, by optimizing water allocations and reducing irrigation water drainage (Jensen, 2007; Perry, 2007; Halsema and Vincent, 2012) at the multiple scales involved (collective network, farm, plot). This includes an improvement of irrigation scheduling (Jimenez-Bello et al., 2000) but also an upgrade of the system or its technology (by adding new devices to an existing system or using new monitoring devices). For instance, center pivot irrigation rates can be regulated to be adapted to field crop heterogeneity, or controllers can be installed to manage sprinkler rotation speeds (Ghinassi and Pezzola, 2014). Another way to take advantage of technology is to adopt more efficient systems, for example, by switching from flood

or sprinkler irrigation to localized irrigation (surface drip, subsurface drip or microsprinkler).

Furthermore, several analysis frameworks are proposed to assess the performance of irrigated systems (Bos et al., 2004; Benouniche et al., 2014; Serra-Wittling et al., 2019), regarding water resource use, productivity. In general, these frameworks are based on "benchmarking" using performance indicators such as water and fertilizer use efficiency or crop productivity. Other theoretical frameworks such as modeling (Laib et al., 2018), life cycle assessment (Pradeleix et al., 2018) or multicriterial assessment (Aldababseh et al., 2018) have been used to analyze irrigated systems. These approaches have brought new insights in understanding performances of various irrigated systems in order to reduce their environmental impacts. However, further actions are still required, due to drawbacks of existing approaches, and the difficulty of implementing a multidisciplinary approach to the subject of irrigation. Indeed, improving the performances of irrigated systems spans a range of disciplines including hydrology, engineering, soil science, ecophysiology or agronomy. Each discipline has the tendency to focus on its own specialty using specific tools, then studies are often fragmented and lacking in comprehensiveness (Hsiao et al., 2007). Hence, mobilizing different types of research tools and analysis frameworks for a unique subject of research is a challenge in irrigation sciences. Although this multidisciplinary approach is difficult to implement, many studies do support that the performance sought in irrigated systems can be achieved using drip irrigation technology. The following sections presents this technology and the state of the art of the research on its performances.

1.2 Drip irrigation: a technology to improve performance of irrigated agriculture

1.2.1 Drip irrigation systems: principle, advantages and limits

Figure 1.3 shows the general layout of a drip irrigation system. The system can be installed either above the soil surface (surface drip irrigation) or below (subsurface drip irrigation). First, water is pumped from the source, and channeled through the distribution network. Then the pressurized water can go through a tank of fertilizer solution and is filtered to prevent the clogging of emitters. Thereafter, it flows through a series of pipes and is discharged into the field through emitters. The delivery into a specific location of the field is controlled by valves.

Drip irrigation systems can be installed temporarily (disposable drip irrigation systems) or permanently (with a lifespan of a couple of years) on the field depending on crop succession patterns implemented by the farmer. It has

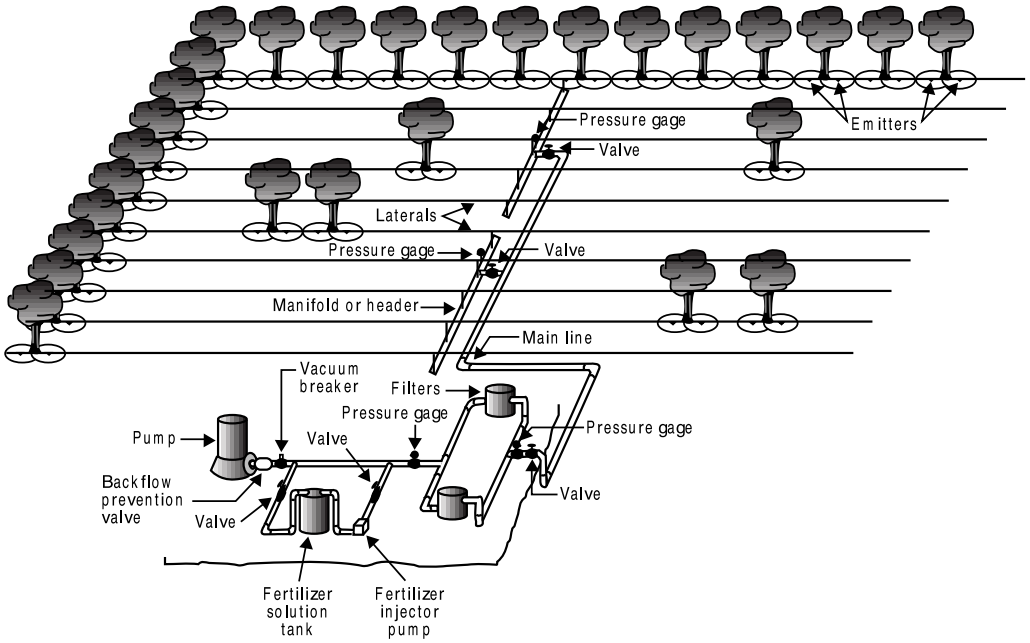


Figure 1.3: Layout of a drip irrigation system (Source: USDA (1997)

gained a great attention in recent years due to the numerous advantages it offers. Indeed, it enables water savings and increased yields through high application efficiencies. It also enables fertigation (the simultaneous application of irrigation and fertilizers), through which fertilizers can easily be applied at the required or critical stages of crop growth. Drip irrigation theoretically allows not only the uniform application of fertilizers but also its frequent application in small quantities, thus it can minimize pollutant leaching. Fertilizer use efficiency can thus be highly improved with such a technology, and groundwater pollution hazards reduced. Hence, it has the potential to simultaneously increase yields and decrease water use and environmental externalities at the plot-scale. In addition, the technology requires less labor, compared to other irrigation technologies. Combined with sensors, it allows the automation of irrigation which facilitates work organization.

Drip irrigation has been promoted and encouraged by many public policies, particularly in the southern Mediterranean, on the basis of these theoretical efficiencies. However, some authors consider the efficient character of drip irrigation as a myth and showed that the use of this technology does not automatically lead to water savings (Benouniche et al., 2014), when different scales and behaviors are taken into account. Indeed, the optimistic gains are often obtained in experimental conditions, and performances in real field conditions may substantially differ. Hence, gains in water efficiencies associated with drip systems are achievable, but in very specific circumstances under narrowly defined operational conditions (Kooij et al., 2013). A number of drawbacks have

been reported for drip irrigation (USDA, 1997). In particular, high risks of emitter clogging, leading to irrigation distribution heterogeneity, and the high costs of installation and replacement have been noted. In general, the installation cost of drip irrigation is greater than that for sprinkler or surface irrigation. Frequent maintenance is essential, and a high level of management is required to obtain optimum application efficiencies. A weak appropriation of fertigation management can cause important decreases in performance. Note that low operating pressures of drip irrigation often results in poor distribution uniformity due to elevation differences in uneven plots. Further, the disposable system causes pollution and waste management problems. Finally, a rebound effect has been associated to this technology by several authors, which rather suggests an expansion of agricultural lands and an increase in water consumption due to the reduction of labor time and higher efficiencies offered by drip irrigation (Venot et al., 2017).

1.2.2 Assessment and improvement of drip irrigation systems: what prospects?

Scientific literature has addressed the issue of improving the technical performance of individual components of drip irrigation, such as the drippers (Lequette et al., 2020), or of the whole system (Laib et al., 2018). Various studies have been undertaken to assess its impacts, most of which have shown encouraging impacts on productivity, and resource use efficiencies (Nikolaou et al., 2020). Halsema and Vincent (2012) and Kooij et al. (2013) showed that the term efficiency has different meanings to researchers and can refer to different elements in the water balance. Indeed, efficiency can refer to crop Water Use Efficiency or Irrigation Water Use Efficiency. It can also refer to irrigation water Application Efficiency or simply Water Productivity. An important issue is to properly define the concept when using it. Depending on objectives, variables used to calculate efficiency differ according to authors. Whatever the definition given to the term efficiency, the actual achievement of efficiency gains (thus decreasing the performance gap) depends on the behavior and practices of farmers actually using the technology. So far, few studies have looked at drip irrigation as used by farmers (Maisiri et al., 2005; Kumar et al., 2009; Thompson et al., 2009). Several recommendations have been made for future research on the assessment and improvement of drip irrigation systems:

- studies must focus on farmer's practices to have more realistic assessments of drip irrigation performance (Benouniche et al., 2014),
- efficiency indicators are scale sensitive and this must be reflected in drip irrigation research (Kooij et al., 2013),

- farmer's practices analyses should consider their broader objectives of livelihood security and agricultural productivity, (Kooij et al., 2013; Laib et al., 2018).
- to go further, one can imagine the need to explore drip irrigation as a vector of more environmental-friendly practices as Kumar and Palanisami (2010) showed it had enabled the emergence of new cropping systems in India.

In agreement with these recommendations, the next section enlarges the debate concerning drip irrigation science by considering that irrigation performance must also include the understanding of farmers practices. Does this technology facilitate the emergency of alternative practices such as those explored within the discipline of agroecology? For more sustainable systems, can the implementation of these alternative practices be part of the solutions to improve the performances of drip irrigation?

1.2.3 Agroecology and irrigated agriculture

Many proponents consider that conventional agriculture, based on the drastic simplification of cropping systems combined with intense uses of chemical inputs, has reached its limits, and many scientists advocate that time has come to think about other production systems to decrease or even eliminate all environmental and health risks (Trabelsi et al., 2015). Hence, there is an ongoing debate about the future development of food systems, and one approach often put forward by different stakeholders (scientists, policy makers, other stakeholders) claims the necessity of implementing more ecologically based farming systems (Migliorini and Wezel, 2017). In this sense, agroecology, a concept that emerged over the last decades, is considered as an alternative form of agriculture, and as one of the possible pathways towards more sustainable food systems.

Definitions

Agroecology suggests that future production systems must enhance economic, ecological, and social performance of agriculture (Gliessman, 1990; Altieri et al., 2012; Wezel et al., 2014; Altieri et al., 2015). It aims at revising the whole production system from production to consumer. The definition of this concept has evolved substantially over the years (Figure 1.4(a)). Indeed, as shown by Wezel et al. (2009), agroecology has been long defined as a scientific discipline consisting in the introduction of ecological concepts in agriculture. But it has gradually emerged both as a social movement and subsequently as a set of practices aimed at protecting the environment (Gliessman, 2007; Wezel et al., 2014; Altieri et al., 2015). According to Altieri (2002) agroecology can be seen as the discipline that

provides the basic ecological principles for studying, designing and managing agroecosystems that are productive and preserving natural resources, culturally sensitive, socially just and economically viable. Hence, agroecology spans a large range of scales and dimensions, from the plot to the agrosystem and the whole food system (Figure 1.4(b)) and covers core elements of each dimension.

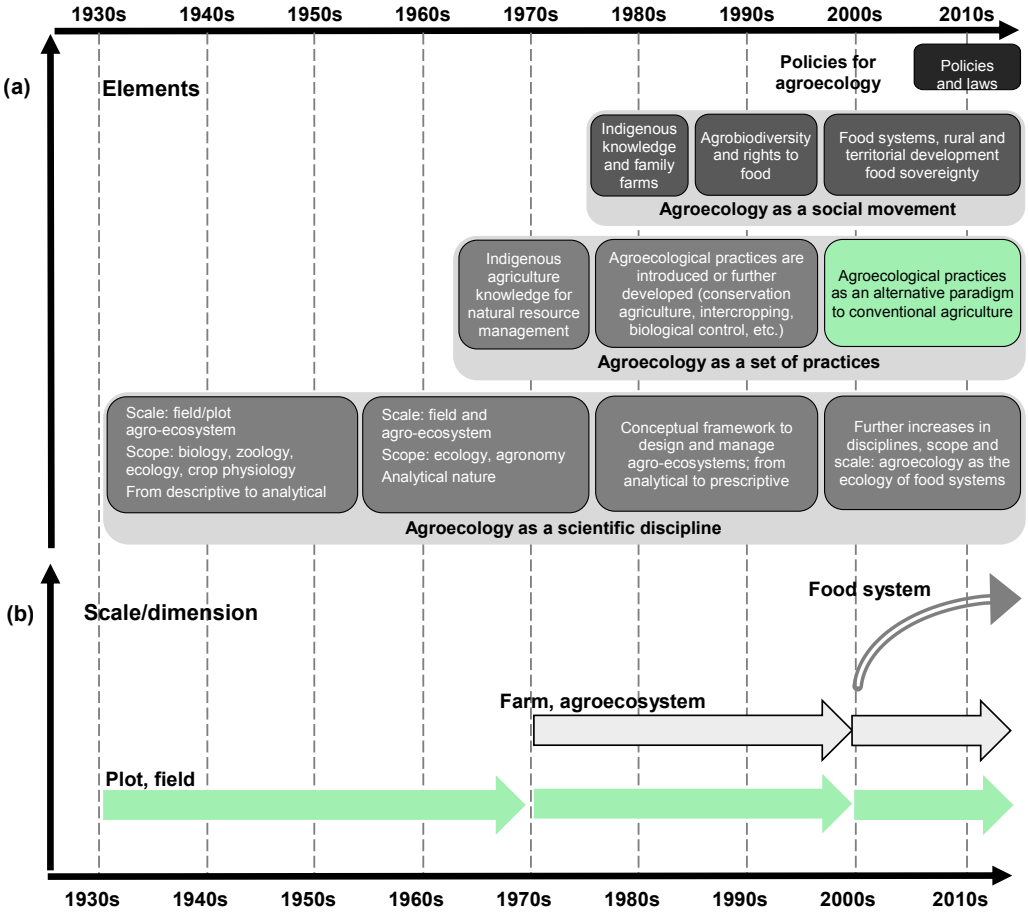


Figure 1.4: Historical evolution of Agroecology (adapted from HLPE (2019)). The dimension and elements focused on in this thesis are colored in green.

A set of principles for agricultural and ecological management of food production systems are associated with agroecology as well as some wider ranging socio-economic, cultural and political principles and elements (Wezel et al., 2020). One of the fundamental principles of that concept is that agroecological systems need to be adapted to each agrosystem and to local pedoclimatic and socio-economic conditions (Migliorini and Wezel, 2017). FAO developed 10 elements of agroecology which are: diversity; synergies; efficiency; resilience; recycling; co-creation and knowledge sharing; human and social values; culture and food tradition; responsible governance; circular and solidarity economy (FAO, 2018).

Furthermore, moving towards agroecological systems occurs in stages depending on the scale of intervention. Hill (1998) proposed the "Efficiency-Substitution-Redesign" (ESR) conceptual framework to analyze the different stages of the transition at plot, farm and agroecosystem scale. According to Hill (1998) and Nicholls and Altieri (2016), efficiency is characterized by reduced consumption and wastage of costly and scarce resources. At the substitution stage, environmentally disruptive inputs are replaced by less environmentally harmful ones. Redesign is the stage where design and management approaches are used to rely more strongly on ecosystem services instead of external inputs. Gliessman (2016) extended the ESR framework to the transformation of the whole food systems, by proposing two additional stage corresponding to changes in consumption patterns and civilization and development (Figure 1.5). The thesis focuses on efficiency stage of the ESR framework and to a lesser extend substitution and redesign stages.

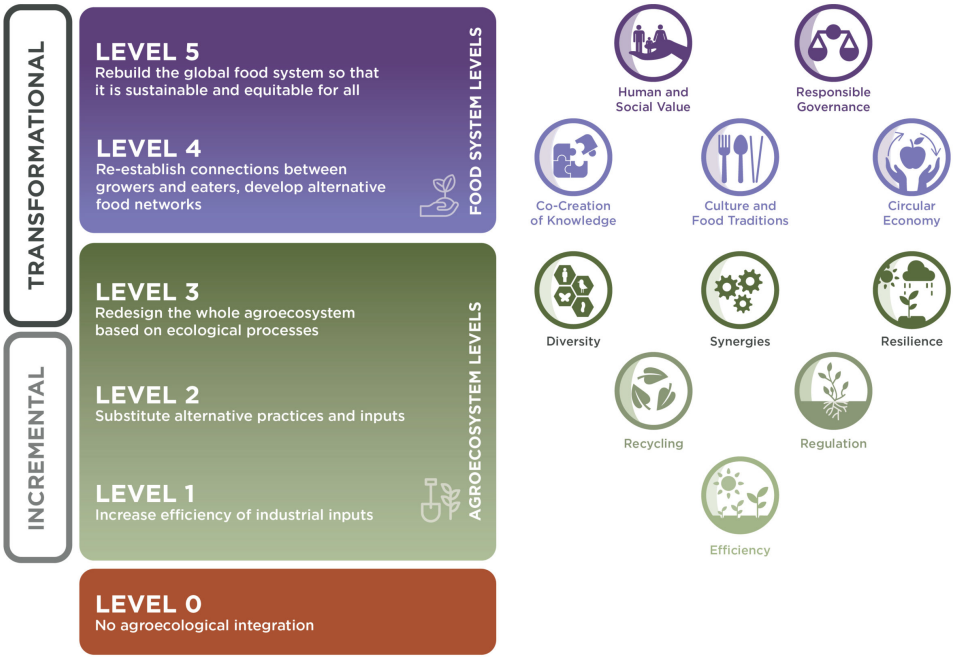


Figure 1.5: The 10 elements of agroecology from FAO (2018) and the 5 levels of agroecological transition (Hill, 1998; Gliessman, 2016)

Agronomic and environmental aspects of agroecology

Agroecological systems seek to return to a more systemic management of the water-soil-plant-atmosphere continuum by intensifying natural processes resulting from the natural biological-physical-chemical interaction between the elements of the system (Bouarfa et al., 2020). It uses four well established ecological principles where external inputs are replaced by natural processes: recycling of biomass, nutrient cycling, biotic pest regulation, water conservation

(Nicholls and Altieri, 2016). Agroecology cannot be restricted to a limited number of standardized practices. Rather, it is a fully systemic approach to sustainability, addressing a transformative change of farming systems (Migliorini and Wezel, 2017). In this thesis, we distinguish agroecological practices and agroecological systems as two distinct concepts. "Agroecological practices" refers to single technical operations implemented in crop management (related to crop, soil, irrigation, pest management, etc.), that aim at increasing total yield or income while enhancing ecological processes and services (Wezel et al., 2014). "Agroecological systems" refer to complete farming systems at plot and/or farm scale, designed based on previously cited agroecological principles, to improve crop productivity while preserving natural resources. They are realized through the application of a combination of several agroecological practices in one farming system.

Agroecology and drip irrigation: state of the art

The principles of agroecology and those of irrigated agriculture are often seen as antagonistic although science and innovation in irrigation have made considerable efforts in technological improvements to limit the impact of irrigated agriculture on the environment. Indeed, irrigation is often associated with a high mobilization of natural resources and dependence on exogenous inputs. Agroecology, for its part, refers to a greening of systems through the mobilization of ecosystem services to limit dependence on exogenous inputs.

Drip irrigation is often presented as an agroecological practice of water saving to reach higher efficiencies (Raffaele et al., 2017; Wezel, 2017). However, the technology does not specifically enhance ecological and ecosystem services *per se*, but greatly decreases reliance on scarce water resources. On an agro-environmental aspect, the advantages of drip irrigation are closely related to agroecology principles, as it increases water and nutrient use efficiencies and crop productivity. For example, the easiness of application of fertilizers offered by drip irrigation can facilitate the substitution of certain chemical or synthetic fertilizers by natural and homemade products such as manure-based tea[1]. Agroecological benefits of drip irrigation can further be enhanced by coupling this technology with other agroecological practices. For instance, the integration of cover crops planted between irrigated crop rows can reduce soil evapotranspiration, decrease erosion and increase soil organic matter and soil nitrogen when leguminous are used (Wezel, 2017). Montalba et al. (2019) showed that organic management based on agroecological principles of drip irrigated blueberry (*Vaccinium corymbosum L.*) achieved higher yield, lower production costs and lower environmental impacts compared to conventional management.

[1] Brinton and Tränkner (1996) define compost teas as “deliberate production of specific (water) extracts based on composts of known properties and age”.

However, such researches are scarce in scientific literature, especially in the Southern Mediterranean region. Indeed, studies aiming to improve performances of drip irrigation systems using the analytical framework of agroecology, and in particular the implementation of agroecological practices, are rare. Furthermore, the future perspectives of research on agroecology in drip irrigation systems need to go beyond the simple improvement of water and nutrient efficiencies and crop productivity. Studies might integrate the understanding of the whole technical management route of the cropping system and in particular, analyzing how novel agroecological practices could be implemented. There is indeed a need to analyze the opportunities offered by this technology to implement agroecological practices and how these can in return enhance the performance of drip irrigation technology. The environmental sustainability of agroecological practices implemented in drip irrigation technology is not straightforward and should be assessed and proven.

1.3 Problems and objectives

Agroecology appears as an alternative solution to cover the challenges of the whole irrigated system. This thesis reassesses the paradigm of its antagonism with irrigation and explores the possibilities to reconcile both concepts in the understanding and improvement of irrigated systems. How can agroecology be integrated into the understanding of irrigated systems using drip irrigation? Is the implementation of agroecological practices in these systems a solution to improve resource use efficiency and address environmental issues? Starting from the postulate that, despite its drawbacks, drip irrigation could become a lever of action towards the agroecological management of crops, this thesis analyzes this technology as a potential vector of interesting practices to initiate transitions towards more sustainable systems.

As the overall goal, it aims at analyzing whether locally existing agroecological practices, integrated within technical management routes (TMR) applied by farmers, can be a lever to improve performances of drip irrigation technology. This objective is applied to an emblematic case-study site of semi-arid irrigated agriculture in the Southern Mediterranean, the Merguellil downstream plain in Tunisia. The thesis involves performance analysis mainly focused on the water and nitrogen budgets and the consequent yield responses of an emblematic crop of the region, taking into account the diverse technical management routes applied, including different agroecological practices. To achieve this general objective, three specific objectives were defined, describing the specific aspects to investigate.

- A thorough and methodical description of the diversity of farming technical management routes (TMRs) to apprehend the existing farming practices in the study zone. The expected output is the characterization of all types of TMRs applied to crops by local farmers according to their farming systems and existing conditions. This diversity can serve as a partial pool of innovations from which novel more agroecologically sound cropping systems could be designed. As such, we seek to characterize locally existing cropping systems in their whole dimensions (through TMRs of which the diversity reflects cropping systems diversity), potentially including both more conventional and more agroecology-compatible farming practices. This step of analysis hence explores the diversity of local farming practices as a potential lever to initiate an agroecological transition, and thus positions itself upstream of most studies related to agroecology in which agroecological practices or systems are built and evaluated.

- An assessment of the agro-environmental impacts of these diverse technical management routes in both qualitative and quantitative manners. The potential environmental sustainability of existing TMRs is first assessed qualitatively. This gives an *a priori* categorization of practices into (non)-environmental-friendly TMRs. Assuming water and fertilizer management as the main factors impacting yield responses in the studied systems, the quantitative assessment then focused specifically on fertigation practices and resulting yield response. Both qualitative and quantitative assessments seek to mobilize approaches from multiple disciplines to treat questions of irrigation, a lack in the research so far.

- The analysis of improvement pathways regarding irrigation performance, through the dual integration of agroecological practices and new patterns of irrigation scheduling. This specific objective focuses on an exploration of pathways to improve the farmers' farming practices through improved management practices and the *in silico* integration of agroecological practices in their current production scheme. Which types of management actions can be undertaken by farmers to have more efficient and productive systems? Which further improvements can be achieved by integrating local agroecological practices into farmers' practices?

The Southern Mediterranean and especially the Tunisian context are adequate environments to treat the problematic presented above.

1.4 Case-study

1.4.1 Irrigation in Southern Mediterranean

The Mediterranean basin has experienced increases in the inter-annual variability of precipitation and temperature, as well as in extreme climatic events in the last decades (Cramer et al., 2018). There have been significant negative trends of the annual precipitation in the majority of regions (Philandras et al., 2011). The Maghreb countries located in the Southern part of the basin are among those that experience the most severe water shortages (Frija et al., 2009). In these areas, water resources and rainfall are irregularly distributed. Thus, the agricultural sector will have to meet, in the coming decades, the challenge of providing both an increased food supply (due to an increasing population with changing dietary habits) and water demands with less available freshwater water (Cramer et al., 2018; Aguilera et al., 2020). Global changes are challenging the sustainability of water resources and the issue is more acute with the consistency in projections of reduced freshwater availability and longer and more frequent droughts (Cisneros et al., 2014). Conversely, agriculture also plays a key role in the distribution of water resources, since it's directly involved in the water cycle through irrigation withdrawals, evapotranspiration, drainage and runoff fluxes (Leenhardt et al., 2020). In this context of spatial and temporal heterogeneity of resources, rainfall still remains favorable to rain-fed agriculture in many regions across the Mediterranean basin. However, irrigation is also necessary and indispensable to respond to agricultural demand in the more arid and semi-arid regions of the basin, in particular regarding market gardening crops. At the farmer's level, irrigation is seen as the main lever of action to increase farm productivity, and thus increase economic incomes (although this is not always the case). To increase agricultural production, irrigation has been encouraged by public policies with the promotion of new technologies such as drip irrigation. Kuper et al. (2016) estimated to more than 500.000, the number of farms supplied by groundwater in Algeria, Morocco and Tunisia. So far, it has been largely adopted by a wide range of farmers including smallholders (Venot et al., 2017). The individualized access to irrigation water or access managed by small collective irrigation networks has enabled farmers to become more autonomous (Dugué et al., 2014). However, even though the development of irrigation in this region has boosted and transformed the economy (Lejars et al., 2017), it is done to the detriment of the less visible but continuously increasing pressure exerted on water resources, all the more so as the irrigated areas are constantly growing (Kuper et al., 2016).

1.4.2 Irrigated agriculture in Tunisia

In Tunisia, agriculture contributes to 8 to 12% of GDP employs 17% of national workforce. It is carried out through 516000 farms with an average size of 10

ha; 75% of the farmers having less than 10 ha. The irrigated sector accounts for about 37% of agricultural GDP (Gafrej, 2016). The country is characterized by an extreme Mediterranean climate (Figure 1.6) with a pronounced gradient between the North (wet) and the South (more dry). Central Tunisia is characterized by an arid and semi-arid climate. Water management has been a crucial element of civilization and development in the country (Hamdane, 2019). Accounting for approximately 8% of agricultural lands, the water demand of irrigated agriculture in Tunisia, as in most countries of the Maghreb, has increased significantly in recent decades, due to the development and the adoption of new technologies (Frija et al., 2009; Venot et al., 2017) and the extension of irrigated areas. Indeed, since the 1980s, the agricultural sector in Tunisia has been undergoing a modernization process characterized by a progressive intensification (regarding resources: lands and chemical products), the use of technologies such as drip irrigation (Gil et al., 2009) and access to ground water resources through individualized pumping systems.

Consequently, water resources are subject to strong pressures, due to i) numerous irrigation development projects, ii) a high increase in the number of individual wells and boreholes and iii) a strong dynamic of expansion of irrigated surfaces, especially in Central Tunisia (Poussin et al., 2007), resulting in a decrease in water table levels (Massuel and Riaux, 2017) in many regions. In Central Tunisia, the Merguellil river downstream plain has one of the most important underground reservoirs in the country, which is easily accessible through modern collective or individual pumping systems. The water table has been experiencing a continuous draw-down for many years (1 $m.year^{-1}$ on average), leading to the drying up of shallow wells. This raises the question of the sustainability of this resource use on the long term, but most especially that of equity of access to this resource (Massuel and Riaux, 2017). Indeed, smallholder farmers who often invest heavily in the development of boreholes, for example, must constantly deepen their wells and consequently, face increasingly high pumping costs (Feuillette, 2001). This development of irrigated agriculture thus appears both as a tremendous opportunity (Collard et al., 2016) but also as a vulnerability for these farmers and farming model.

Furthermore, as the modernization of agriculture has been at the center of national policies since at least the 1980's, conventional intensification through increased use of external chemical inputs and development of irrigation has become widespread. The aim was to transform the production systems so that the most efficient technologies can be applied efficiently and profitably (de Lattre-Gasquet et al., 2017). The agricultural policy was, then, oriented to encourage the production of food products in which Tunisia had a competitive advantage (olive oil, fruits, vegetables, etc.). The resulting production systems were lowly

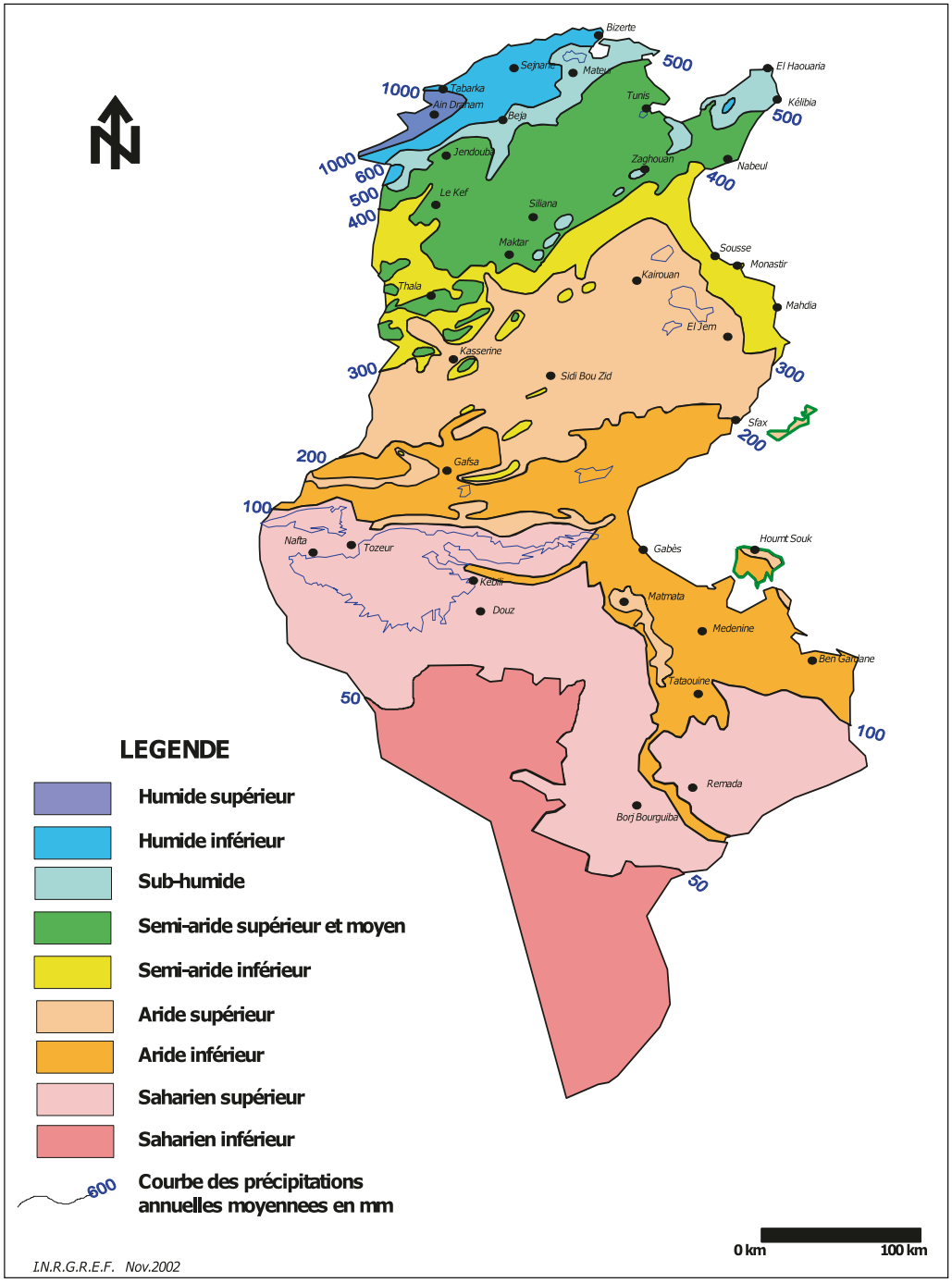


Figure 1.6: Map of Tunisia showing the the climatic zones (from Hamdane (2019))

self-sufficient (Gil et al., 2009), and dependent on external, often imported, inputs (fertilizer, seeds, pest management products). According to Gafrej (2016), most of these production systems are implemented in fragile natural conditions. They therefore have a relatively high environmental cost. This author and de

Lattre-Gasquet et al. (2017) highlighted the numerous agro-environmental issues that irrigated agriculture is confronted to in the country, in particular:

- the use of high salinity water and the drop in fertility of irrigated soils;
- the pollution in irrigated soils primarily due to misuse or inadequate use of mineral fertilizers and pest management products. Soil structure and biology degradation under the double effect of climatic hazards and agricultural practices, causes decrease in their water retention capacity;
- the agronomic model in Tunisia meets constraints of growth and stabilization of production.

Under these conditions, the current Tunisian irrigated agriculture and its hypothetical further expansions, without adapting and improving farming practices, poses a problem of sustainability of both production and resources. This dimension is one of the key issues in the research for the sustainability of agriculture, whether economic or ecological (Gafrej, 2016).

1.4.3 Agroecology in Tunisia state of the art

In Tunisia like in all the Maghreb countries, research on agroecology especially in irrigated systems are scarce. To date, less than fifteen paper can be found on the topic in the Tunisian context (L. Hossard, unpublished data[2]). Among the available literature, Altieri and Toledo (2005) highlighted examples of farming systems developed by smallholder farmers in the country, well adapted to their local social and climatic conditions. These included agroforestry and traditional water harvesting (Figure 1.7).

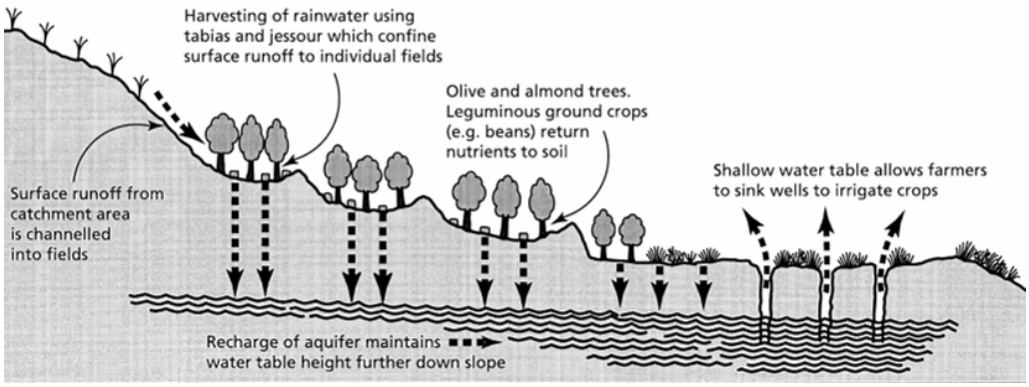


Figure 1.7: Traditional water harvesting in agroecosystems of Tunisia (Altieri and Toledo, 2005)

[2]Bibliography research using the word "agroecology". Literature on more specific subjects related to agroecology (and not mentioning the word) exist.

According to de Lattre-Gasquet et al. (2017), Tunisian farmers are mostly favourable to a transition towards an agroecological use of agricultural lands. Souissi et al. (2017) found that diversification (Figure 1.9) characterizes Tunisian farming systems and is a source of resilience to climate change. These diversified systems mostly grow cereals, vegetables, and forage crops combined with livestock. These authors are supported by Ameur et al. (2020), who identified a set of agroecology-compatible practices (the use of homemade liquid manure in fertigation, integration of legumes in crop successions, relay intercropping, agroforestry, crop diversification, livestock integration) in central Tunisia based on the analysis of local farming practices. These are mostly implemented to improve soil fertility, increase per surface agricultural production or enhance ecosystem services. In general, agroecology remains a wide field of research to explore in Tunisia (like in all the Maghreb countries). There is also a gap in the literature regarding the analysis of farming practices in a systemic approach considering the whole management rules or cropping systems. The assessment of impact of farming practices in terms of resource use (water and N for instance) and productivity are also scarce. Although Karray et al. (2008) studied olive grove-market gardening intercropping systems as practice to improve water use efficiency, there is so far, few studies, to our knowledge, focusing on agroecology (in a broad sense) as a solution to overcome the challenges of irrigated agriculture in Tunisia.

1.4.4 The Merguellil downstream plain

Central Tunisia, despite its semi-arid climate and high variability of rainfall, represents an area of great potential for agricultural development, between the already well-exploited Northern and the arid Southern parts of the country (Leduc et al., 2004). Within this region, The Merguellil downstream plain also called the Kairouan plain (Figure 1.8) has an important aquifer reservoir which represents an essential asset to compensate for climatic fluctuations. Most of the irrigation water withdrawals in the plain are carried out in the downstream plain. The plain has a strong agricultural vocation (Figure 1.9), with very varied crops of market gardening (tomato, pepper, watermelon, melon), arboriculture (olive groves, fruit growing) and winter crops (wheat, barley, potato, onion, beans).

Irrigation is based on traditional know-how and has long been practiced through public irrigated perimeters, and since the 1980's through private shallow groundwater wells. The challenges of irrigated agriculture in this region (variable and limited resources, increasing withdrawals, weak control of access to water, pollution, etc.) are similar to those of the entire Mediterranean basin. The Merguellil downstream plain is an emblematic case-study where numerous hydrological, agronomic and economic research related to agriculture and

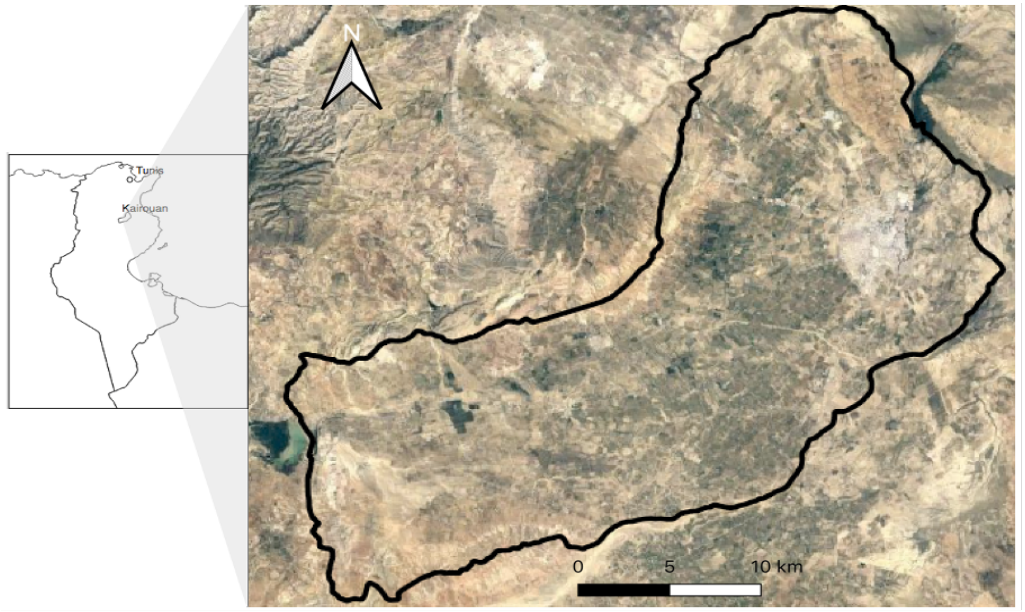


Figure 1.8: The Merguellil downstream plain

water uses have been carried out in the last decades. Nevertheless, impacts of farming practices and local agroecological practices are little known. Thus, the area lends well to explore the relevance of the use of agroecological practices to improve drip irrigation.



Figure 1.9: The Merguellil downstream plain landscape (Photo: O. Grunberger)

1.5 General methodology

This thesis spans disciplines of agronomy and irrigation sciences. Agroecology brings transdisciplinarity (Ruiz, 2006) and enables to explore multiple dimensions within an integrative work. To treat the research questions of the thesis, we first defined a scale of analysis as well as the main elements representing it. Thus, as a study system (Figure 1.10), this thesis focuses on chili-pepper fields, the related technical management rules (TMRs) and biophysical processes (hydrological fluxes, plant growth). The main scale considered is the plot, considered as the primary entity in which farmers manage a crop, and the scale at which major hydrological fluxes are defined. Farmers play a key role in this system as they design the TMRs and manage the fields. This study system is however set within the farm (interactions with other entities for resources sharing for example), scale at which some analyses are undertaken. Chili-pepper

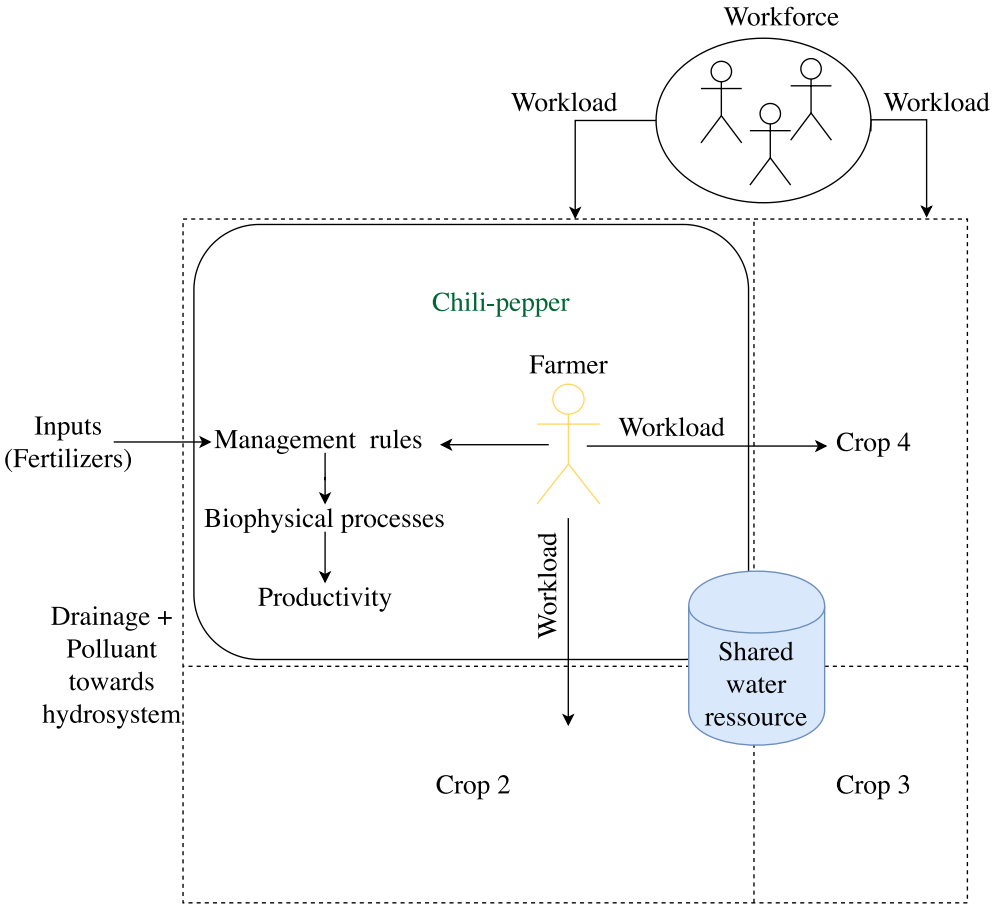


Figure 1.10: Studied system boundaries.

was chosen as it is an emblematic crop, representative of conventional farming practices in the Merguellil downstream plain. Indeed, vegetable crops, mainly conducted with drip irrigation, are among the primary sources of agricultural

pollutants and water consumption in the South Mediterranean irrigated areas (Suárez-Rey et al., 2019) and in the Merguellil downstream plain. Further, chili-pepper is widespread in existing cropping systems, and represents about 35% of vegetable crops' surface in Central Tunisia (CRDA, 2017; unpublished data).

The global methodological approach adopted to realize the three objectives of analysis, previously described, applied to our study system is an adaptation of the Bos et al.'s framework (Bos et al., 2004) (Figure 1.11) for irrigation performance assessment. The latter enabled to conceptualize each specific objective and choose adequate methods of analysis to use. The framework is declined into five stages based on a series of questions. The first stage, the definition of the purposes and strategies, looks at the broad scope of the study. The following stage is the design of the study, were the required data are defined, criteria and indicators are selected. Then the planned program is implemented with data being collected, analyzed and presented. The fourth stage is to act on the information provided by the analyses, with a variety of actions possible, including inter-comparison of systems or the proposition of pathways to improve the systems. The final stage is to assess whether further investigations are required. This framework has been applied to each specific objective independently. The choice of the approaches and tools hence depended on the specific objectives and the data to be collected for each one. Multiple approaches and tools were used depending on the specific objective, including typology; qualitative and quantitative assessment through interviews, field monitoring and observation; as well as modelling.

Analyses focused on farmers' management rules, how these affect the biophysical processes and resulting productivity. The description of management rules involved in chili-pepper crop production was realized through a typology analysis. This analysis provided information on the types of management rules and integration of agroecological practices within chili-pepper cropping systems. A thorough field monitoring of fertigation strategies was then undertaken considering these strategies as one of the most important impacting productivity. This enabled to collect data to model and assess farmers' fertigation strategies using Optirrig, a crop model dedicated to fertigation context. Finally, we explored pathways of improvement of farmers' fertigation practices by testing different scenarios. Detailed methodologies are given in each chapter.

1.6 Manuscript layout

The manuscript is constituted of four chapters pertaining to the research results of this thesis (Chapters 2 to 5) and a final chapter (Chapter 6) giving a general

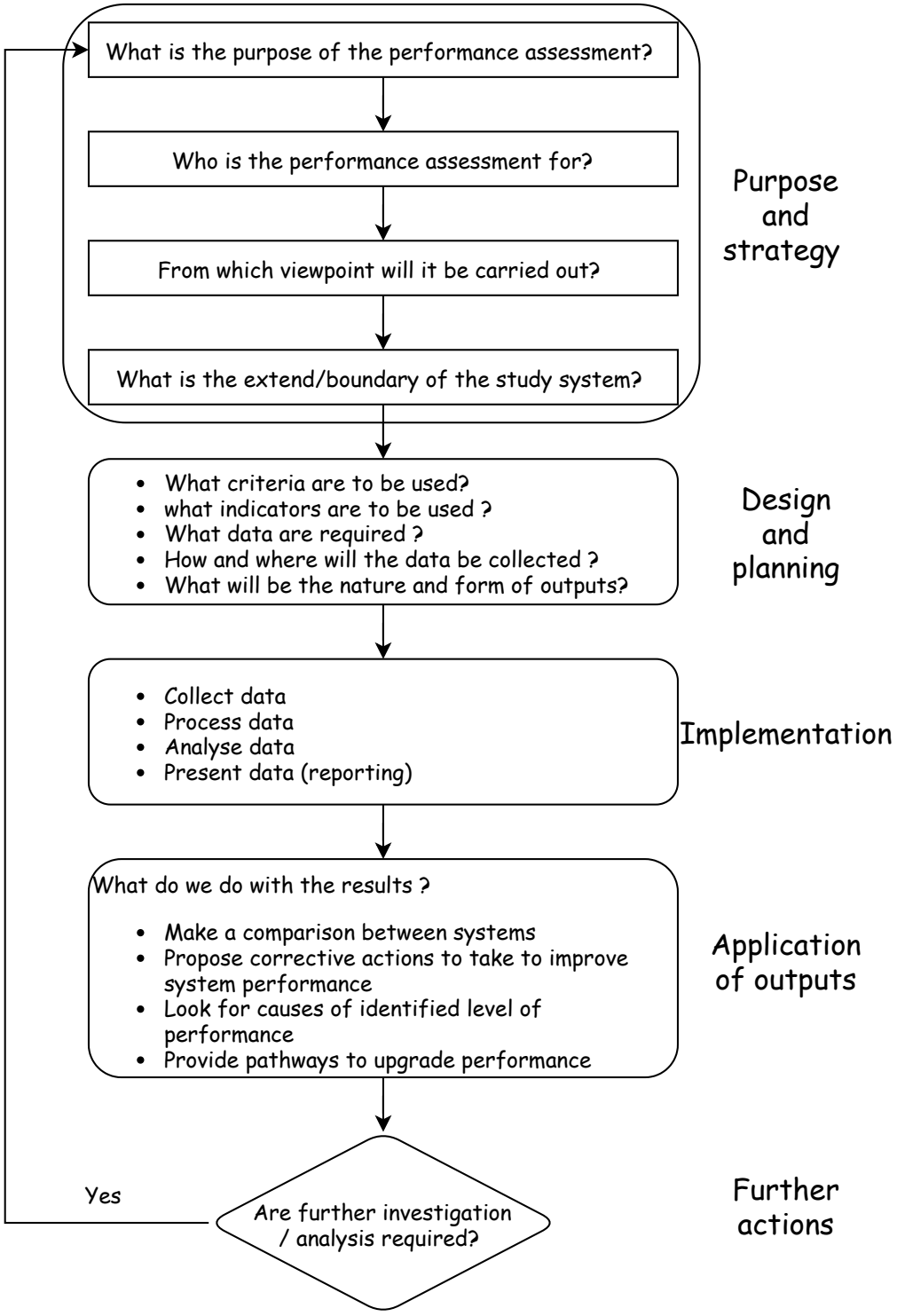


Figure 1.11: Framework for performance assessment of irrigation adapted from Bos et al. (2004), applied to each specific objective.

discussion of the results. The manuscript currently includes one accepted scientific article (Chapter 2), while Chapter 4 constitutes a second submitted article.

In order for them to form coherent ensembles, objectives as described in section 1.3 are dispatched within these chapters. The description of the diversity of farming practices and the qualitative assessment of their potential environmental impacts is treated in Chapter 2. Chapter 3 presents the field data collected to perform the quantitative assessment of the environmental impacts step, which is then treated in Chapter 4. The analysis of improvement pathways is implemented in both Chapters 4 and 5.

Chapter 2: Challenging agroecology through the characterization of farming practices' diversity in Mediterranean irrigated areas
The purpose of this chapter was to i) describe the possible diversity of TMRs and identify, within these, the existence of environmental-friendly ones and agroecology-compatible practices or sets of practices. Additional investigations were performed to determine the types of farmers implementing these TMRs. A series of surveys was undertaken on 45 chili-pepper plots, and data related to the corresponding farm structure were collected. The sampling was carried out to cover a wide range of farm types, socio-economic and pedo-climatic conditions. Statistical analyses were realized to formalize a typology of management rules. Structural data at the farm scale allowed to partly determine the main characteristics of farms and of farmers implementing each type of TMR. The potential environmental impact of each type was assessed through a qualitative assessment approach used in ecological sciences. This chapter is written in the form of an original paper and submitted to the European Journal of Agronomy.

Chapter 3: Field monitoring
This chapter describes the field data collected to quantitatively assess the TMRs. It presents a set of crop management data collected in an uncontrolled environment. Eleven fields, selected based on the results of the previous analyses were monitored. Data related to irrigation and fertilization (dates, amounts), yields, etc. were collected. Field data are particularly inaccurate. Thus, the uncertainty related to each type of data was described and quantified. Then, a first analysis of yields and some crop management data was realized.

Chapter 4: Modelling and assessing environmental impacts of fertigation practices under field conditions: a case-study of chili-pepper using the Optirrig model
This chapter analyses the relevance of a modelling approach to assess farmers' practices based on data collected in real conditions (poorly-gauged fields). A methodological approach is proposed to perform such an analysis. Then, we assessed the agro-environmental impacts of farmers' fertigation practices through

a set of indicators of resource use efficiency and productivity including water productivity, water application efficiency, nitrogen use efficiency, etc. An algorithm of optimization of irrigation was proposed and applied to each field to generate optimized irrigation strategies reducing drainage and increasing yield. Further, these optimized irrigation strategies were compared to farmers' strategies. This chapter has been submitted to the Agricultural Water Management journal.

Chapter 5: Sustainability of drip irrigation systems: toward an improvement through agroecological practices
This chapter aims at analyzing further optimization strategies through an hypothetical implementation of agroecological practices. As emblematic local agroecological practices, the use of manure tea (MT) and intercropping of chili-pepper within olive groves were selected. As an exploratory analysis, we assessed the potential interest of the introduction of these two practices and optimized irrigation strategies in each modelled chili-pepper cropping system in terms of environmental impacts (water and nitrogen budgets) and economic viability.

Chapter 6: General discussion and conclusion

This chapter highlights the important contributions to initiate the first stage of the ESR transition process in the Merguellil downstream plain. Although further investigations are required, new insights are brought by the thesis in terms of agroecological perspectives in irrigated agriculture allowing to better shape the research agenda in irrigation and agroecology in Tunisia and the Maghreb in general.

Chapter 2

Challenging agroecology through the characterization of farming practices' diversity in Mediterranean irrigated areas

Abstract

Identifying locally adapted and adopted efficient practices can be a step towards the agroecological transition of irrigated plains of the Southern Mediterranean region. However, these types of practices - often little known - are drowned within a wide range of practices. The objective of this study was, first, to elaborate a method to describe this diversity in a semi-arid irrigated landscape, at both the plot and farm scales; second, to show the main characteristics of these types of crop management; and third, to question their sustainability according to agroecological principles. To do so, this paper focused on Southern Mediterranean irrigated cropping systems as i) studies on management routes are scarce with regard to this region; ii) irrigated landscapes are known for their high level of natural, technical and financial constraints, often favoring more intensive farming practices regarding chemical inputs. A series of semi-directive interviews were conducted in order to assess farmers' management of chili-pepper-based (Capsicum annuum) cropping systems, a widespread crop in the Merguellil plain, Central Tunisia. The "Typ-iti" method, combining multivariate analysis, clustering and association rules, was used to characterize the diversity of technical management routes (TMR) of these systems. The environmental sustainability was qualitatively accessed by classifying the clusters of TMRs obtained according to their potential impact on natural resources. Then, these management routes were qualitatively associated to some farm structural

indicators, to analyze their diversity at the farm level. These enabled to distinguish a gradient of farming practices and characteristics, respectively at both plot and farm scales relative to environmental impacts. The study showed that some environmental-friendly TMRs coexisted with conventional TMRs for chili-pepper-based cropping systems. Our method characterized three main groups: i) a group of intensive TMRs regarding chemical input powered especially by tenant farmers, ii) an intermediary group iii) a moderate group powered by land owners. Throughout these main groups, seven types of TMRs were described. These were always comprised of both agroecology and non-agroecology-compatible technical operations. This coexistence of diversely impacting practices challenges agroecology in multiple ways. Fertilization management appeared as a major issue in the study zone, often resulting in high applied doses. These findings could allow actors in charge of agriculture to better focus their action. However, the study did not take into account the outputs of the studied systems, so that their productivity and environmental impacts have not yet been assessed in a quantitative manner. For future studies, the paragons obtained from our analysis are typical cases that could be studied for such a purpose.

Key words: cropping systems; environmental impact; irrigation; Merguellil plain; Tunisia; typology.

2.1 Introduction

The Southern Mediterranean region is vulnerable to climatic hazards and at a high risk of severe degradation of both biodiversity and agricultural production, due to the combination of climate change and conventional farming practices (Migliorini et al., 2018; MedECC, 2020). New patterns of action would be required to address these issues simultaneously (Caron et al., 2014), with an acute need to implement new agricultural models combining biodiversity conservation, climate change adaptation and food production. Agroecology, which is the production of significant amounts of food, valorizing ecological processes and ecosystem services and integrating them as essential factors in the improvement of practices (Gliessman, 1990; Wezel et al., 2014; Altieri et al., 2015), with its three pillars i) efficiency increase, ii) substitution of inputs, iii) system redesign or diversification (Hill, 1998; Wezel et al., 2014; Duru et al., 2015; Ci and Ma, 2016), could be a pathway for a more sustainable agriculture in the Southern Mediterranean region (Horlings and Marsden, 2011). Agroecology suggests that actions to achieve this goal must be adapted to each agrosystem and take into account local conditions.

Although recent literature is appearing on the subject (for example, de Lattre-Gasquet et al. (2017) and Ameur et al. (2020), little is still known on the potential

of agroecological concepts to address these issues in this region of the world, in particular within irrigated areas. In the North African irrigated areas, agriculture is strongly based on the use of external productive factors (especially chemical inputs). Efficiency increases and input substitutions could appear as a first step of action towards a more sustainable agriculture. This can start by a widespread adoption of local efficient and environmental-friendly farming practices. In this paper, it is hypothesized that strong social, economic and environmental constraints in irrigated areas (Jamin et al., 2011) might enable a diversity of farming practices. Could more environmental-friendly farming practices arise from this local diversity? In what extent are these practices already present or how can they be developed in Mediterranean irrigated systems? In a first step to answer these questions, the objective of this study was to i) describe the possible diversity of farming practices in a typical North African irrigated area and ii) identify the existence of environmental-friendly management routes, and the types of farmers implementing them. The paper seeks to provide a complete and comprehensive description of existing farming practices at the plot and farm-scale, enhancing their diversity, and putting forward in particular potential agroecological practices, but does not undertake a quantitative evaluation of their agronomic or environmental impacts.

Access to irrigation is a recurrent demand of smallholder farmers in North Africa, due to expected productivity and income increases, compared to rainfed systems. Progress has been made in this matter, with the development of individual pumping systems giving access to the aquifers. The number of pumping wells has indeed increased drastically in North Africa, irrigating more than 1.75 million ha in Algeria, Morocco and Tunisia (Leduc et al., 2004; Kuper et al., 2017). The Merguellil plain in Central Tunisia is a typical example. In parallel, public policies sought to encourage water economy and have promoted the development of modern irrigated systems, resulting in a wide adoption of drip irrigation. But through fertigation, the latter also facilitates increased applications of nutrients, at a certain environmental cost due to pollutions (Burkhalter J. Philip and Gates Timothy K., 2005; Poussin et al., 2007; Laib et al., 2018). However, it has been shown that the modern irrigated systems could also enable a better management of nutrients and inputs (Benouniche et al., 2014; Al-Ghobari and Dewidar, 2018; Sandhu et al., 2019).

In addition, smallholder farmers such as those in the Merguellil plain, can design environmental-friendly farming practices, more adapted to their local social, economic and environmental conditions, allowing them to achieve their production goals, depending on neither chemical inputs nor pesticides (Altieri et al., 2015). To achieve this, farmers often combine different strategies as part of a usual household management scheme (Pinto-Correia et al., 2017). Thus,

the farmer makes choices through diverse ways of farming. So, it is fair to ask whether diversity is one of the main characteristics of these farming practices at the territorial scale.

In this paper, we elaborate a method to describe the diversity of farming practices in the Merguellil plain – a location of multiple researches, characterized by its dynamic and diverse agricultural system (Azizi et al., 2017) – at both the plot and farm scales, by analyzing local practices. This can be achieved by characterizing existing technical management routes (Renaud-Gentié et al., 2014; Salou et al., 2017), noted TMRs, and identifying a gradient between chemically-intensive and more environmental-friendly TMRs. TMRs are the logical and ordered succession of technical operations (TO) aiming to control the environment and obtain a given production (Sébillotte, 1974). So far, investigations that integrate all the TMRs steps to describe existing cropping systems in small-scale household agriculture are scarce (Renaud-Gentié et al., 2014; Czyrnek-Delêtre et al., 2018), even the more in Mediterranean irrigated areas. Multiple studies characterizing farming systems and crop management practices exist (Bellon et al., 2001; Köbrich et al., 2003; Maton et al., 2005; Poussin et al., 2008; Blazy et al., 2009; Ibidhi et al., 2018). These studies used either statistical analysis or participatory and expert-based methods. These methods have limits as they i) only identify the most relevant character of each TMR; and ii) do not describe the logical links between TOs (Renaud-Gentié et al., 2014). For instance, only quantitative data on farming practices were used to describe the diversity of coffee-based agroforestry systems in Costa-Rica (Meylan et al., 2013). Another study, examining the variability of farm structure and farming practices, highlighted both low input and intensive systems, but was limited to the analysis of water and N use, pest and crop residue management (Caballero, 2001).

The paper, focused on chili-pepper (Capsicum annuum) as a cropping system model, proceeds in the following way. First, it develops the approach used to assess farmers' practices. Then, it describes the technical operations, their interconnexions within TMRs, and their (non-)agroecological orientation and (non-)association to farm types. Finally, it discusses this diversity of farming practices in the light of co-existing irrigation, pollution and agroecology stakes, and how these conditions challenge the implementation of agroecological practices in Southern Mediterranean irrigated areas.

2.2 Materials and methods

2.2.1 Study site

The study took place in the downstream plain of the Merguellil catchment in Central Tunisia (Fig. 2.1). The latter, covering over 700 km^2, is part of the large

and flat Kairouan alluvial plain which extends almost over 3000 km^2 (Leduc et al., 2007). The climate is semi-arid with 300 to 500 mm of total annual rainfall. The downstream plain is almost entirely used for agricultural purposes with a combination of irrigated and, to a lesser extent, non-irrigated agriculture. Most agricultural water withdrawal, consuming 80% of the total extracted water per year (Poussin et al., 2008), takes place in this downstream zone where a very high density of drilling is observed (Massuel et al., 2017). Cropping systems are characterized by a wide variety of crops, including olive groves and fruit orchards, alone or intercropped; watermelon (Citrullus lanatu) and melon (Cucumis melo), tomato (Solanum lycopersicum), chili-pepper (Capsicum annuum) and other winter and summer vegetables (Poussin et al., 2008; Ameur et al., 2020). Farm structures are also diverse as far as total area, level of equipment and cropping systems are concerned. The agricultural sector is very dynamic, characterized by significant changes in farms' production structures and orientation during the last decade. These changes were stimulated by i) a facilitated water access for initially rainfed farms; ii) the adoption of irrigated horticultural crops for some farmers; iii) the reduction of annual crops, replaced by irrigated olive groves and fruits orchards for others (Azizi, 2018). As one of the most widespread crops, present in most of cropping systems, chili-pepper-based cropping systems were used to represent the irrigated horticultural crops in this area.

2.2.2 Methodological approach

In this paper, farming practices include the ways of farming at both plot and farm scales. The TMR (Technical Management Routes) is a succession of TOs (Technical Operations) applied to a chili-pepper plot. A TO refers to an action or a choice performed by the farmer on the plot. Agroecology-compatible TOs or practices refer to TOs compatible with agroecology. (Non)-environmental-friendly TMRs refer to TMRs compatible with agroecology or not.

The global approach, allowing to finely characterize the TMRs, give indications on their sustainability and links to farm characteristics, consisted in four successive steps: i) sampling and data collection through field surveys, ii) database and variables construction, including a characterization of their potential environmental impact (in a qualitative manner), iii) statistical analysis including data mining, enabling the description of different clusters of TMRs, and iv) the identification of the types of farms implementing each type TMR. These steps are described here below in detail and on Figure 2.2.

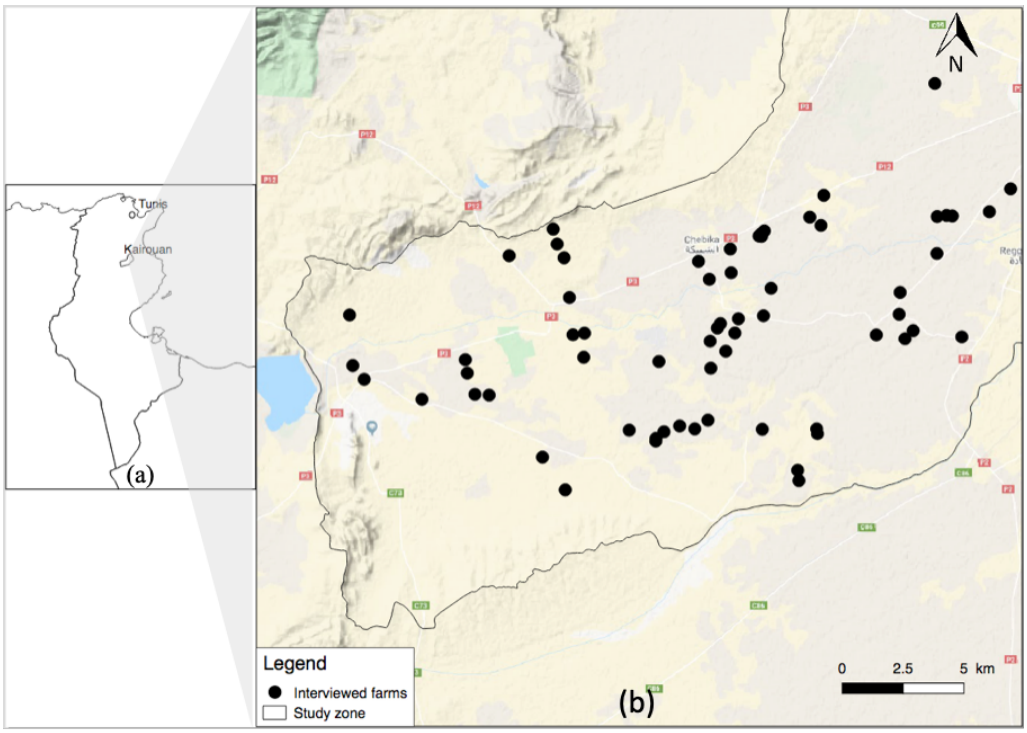


Figure 2.1: (a) Location of the case-study site: the Merguellil downstream plain in Central Tunisia; (b) interviewed farms (black dots).

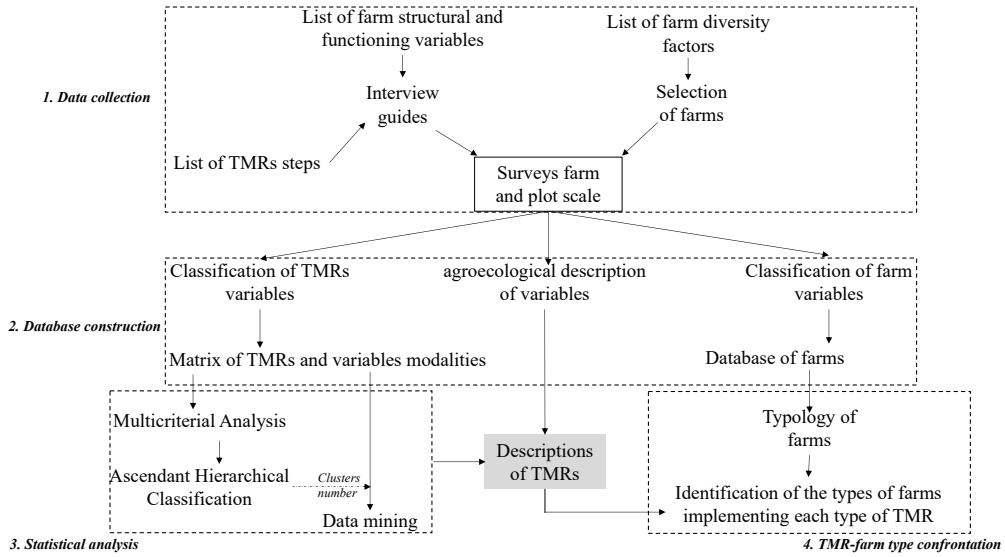


Figure 2.2: Methodological approach.

2.2.3 Sampling and data collection

Data collection was carried out through semi-directive interviews with farmers in Spring 2018 and was conducted in three phases. First, 65 farms were chosen for their diversity, not only in their structure (crop types, farm size, land tenure), but also in their localisation throughout the Merguellil plain. A wide range of farm sizes was covered (1-75 ha). Farm selection was actor- and expert-based, or by direct observation. Second, a series of semi-directive interviews with farmers were conducted, in order to apprehend the organization and functioning of the farms. These interviews concerned not only crop types and successions, but also labor origin (family or temporary), land tenure (tenants, landlords, sharecroppers), water supply sources (individual drilling, collective network), and crop management (seed origin, chemical fertilizers, plant protection products). This allowed a confrontation of management routes to farms structures. Third, a series of detailed interviews were conducted on the chili-pepper crop farming practices, using the TMR concept applied to both farmers' strategic and operational decisions. The strategic decisions are made at the beginning of the season and concern plot configuration, types of association, choice of crop varieties and planting date, while the operational decisions concern the technical steps of transplantation, tillage, irrigation, pest management, fertilization and harvesting. A list of TOs related to all the steps of a TMR was pre-established through expert-knowledge and was pilot tested with a few farmers. Data acquisition on the TMRs applied to chili-pepper was carried out on 45 plots. To achieve so, a minimum of two interviews of one to two hours with each the farmer was required in order to correctly understand the functioning of the cropping system. Interviews, combined with direct observations, were face-to-face and took place within the farm, with audio record and field notes. When required, additional information were obtained by phone call.

2.2.4 Database and variables construction

Collected data were transcribed into a table of TMRs, where each TO of the TMR was described by its modalities. The TOs represent the variables used for statistical analyses. The modalities of a TO are the different values it can take. Data were both quantitative and qualitative. The quantitative data were first transformed into qualitative variables, using the "natural occurring division" approach (Husson et al., 2017), based on the analysis of the histograms of the observations, in order to maintain the modalities as observed. Two to four modalities were constructed depending on TOs. To avoid redundant information and characterize the diversity of TMRs, TOs with a single common modality to all farmers were not taken into account in the analyses.

2.2.5 Qualitative assessment of the potential environmental impact of farming practices

In order to assess the potential environmental sustainability of the TMRs, the modalities of each TO were qualitatively classified according to their potential impact on natural resources, using three levels: TOs with a potentially positive environmental impact (e.g. no pesticide application), TOs potentially harmful (e.g. high value of N input) and TOs with no evident positive nor negative first-order impact (e.g. planting date). TO modalities were classified relative to each other, assuming a gradient of environmental impacts rather than an absolute value. Their attribution into each level was based on described agroecological practices in the literature (Wezel et al., 2014; Ameur et al., 2020), and expertise. A rating was assigned to each TO: +1 for TOs with potentially positive environmental impact (agroecology-compatible), -1 for potentially harmful (non-agroecology-compatible) TOs, 0 for TOs with no evident positive nor negative first-order impact. TOs were classified as harmful or not based their contribution to the stages of the ESR (Efficiency increase, Substitution, Redesign) conceptual framework, and criteria presented in Table 2.1. This scoring was adapted from an approach of scoring farming practices for a qualitative assessment of ecological impacts of cropping systems (Bohanec et al., 2008). After statistical analysis, a total rating was computed by summing up the scores of the TOs significantly linked to each cluster, giving a potential level of environmental impact of the cluster. Four degrees of impact were defined for farming practices: high (non-environmental-friendly), neutral (intermediary), medium low (moderately environmental-friendly), and low (environmental-friendly).

2.2.6 Statistical analysis using the "Typ-iti" method

The "Typ-iti" analytical method (Renaud-Gentié et al., 2014) was used to characterize the diversity of TMRs for pepper cultivation. Combining three different statistical tools, the former was realized through three phases: i) a multiple correspondence analysis (MCA) summarizing the relationship between plots and TOs' modalities ii) an ascending hierarchical classification (AHC) enabling the grouping of TMRs into separate clusters, within which the TMRs are relatively similar, finally, iii) a data-mining analysis to generate association rules between modalities (Agrawal et al., 1993). The results of all the statistical analyses are synthetized in a table describing each type of TMR.

MCA was first applied to the TO table. Then, using the resulting coordinates of TMRs on the MCA axis, the AHC was performed by the Ward method, to obtain the clusters. The number of clusters, first chosen on the basis of the explained inertia rate, was consolidated through the calculation of the optimal number of clusters using K-Means partitioning. The description of clusters was,

Table 2.1: Criteria used to classify TOs as "harmful" or agroecology-compatible or not). Each TO is categorized according to the ESR conceptual framework. E= Efficiency increase; S = Substitution; R = Redesign

TMR step	TO	ESR	Criteria
Tillage	Weeding/Hoeing	E, S	Reduces energy consumption for seedbed preparation and soil compaction
Variety choices and crop spatial distribution	Variety	E, S	Increase in pest control, and resistance to water stress. Reduction of fertilizer or pesticide use
	Planting strategy	-	-
	Association with leguminous	E, S, R	Increase in land productivity. Reduction of pest and disease impact. Improvement of nitrogen content of soils
	Association with trees	E,S,R	Increase in land productivity. Decrease in nutrient leaching and soil erosion. Diversity of production: wood (timber, firewood), Protection of crops from intense solar radiation and wind
Irrigation	Water stress	E	Enhance plant water uptake. Decrease water use
Pest management	Number of pesticide applications	S	Pest pressure control with limited use (or no use) of pesticides
Fertilization	Organic fertilization mode	E, S	Reduction of chemical fertilizer use. Reduction of energy consumption for transport when using on-farm manure or from nearby
	N (kg.ha-1)	E, S	Reduced fertilizer use increases efficiency. Reduction of risk of ground and surface water contamination.
	P (kg.ha-1)	E, S	
	K (kg.ha-1)	E, S	
	Ca (kg.ha-1)	E, S	
	Mg (kg.ha-1)	E, S	
	Ternary fertilizer leaf application	E, S	
	Synthetic biostimulant use	E, S	Reduction of fertilizer use. Improvement of nutrient availability
Harvesting	Harvest regularity	-	-
	Crop residue management	E,S,R	Organic matter and nutrient recycling
	Crop color harvest	-	-

first, based on chi2 correlation tests. A modality was linked to a cluster if its p-value < 0.05. Second, a TO modality was described as a cluster's character if i) it was present in more than 50% of the cluster's TMRs, or ii) if more than 50% of all TMRs of the dataset were present in the cluster's TMRs in the case of significant p-value.

Finally, to have a complete description of TMRs, a data-mining analysis was performed. It consisted in mining association rules, which are combinations

of modalities within TOs. This allows to identify additional TOs significantly linked to TMRs and not shown by the previous MCA analysis, because they were not specific to groups. Rules are defined as a succession of TO modalities common to a minimum defined number of TMRs in a same cluster. They were interpreted based on three criteria: the support (S), the confident (C) and the adjusted support, noted Sa (Renaud-Gentié et al., 2014). The support is the frequency of occurrence of a rule. Let us consider A, a succession of k TOs (k > 0), and B another succession of n TOs (n > 0); for A and B, the support of the rule A $\Rightarrow$ B is computed as follows:

S (A $\Rightarrow$ B) = P(A $\cup B$)

A minimum support Sm was calculated by dividing the number of TMRs in the cluster comprising the lower number of individuals over the total sample size. The confident of the rule A $\Rightarrow$ B is the percentage of rules containing A and B.

Confidence (A $\Rightarrow$ B) = P(B|A)

The adjusted support is the support relative the number of TMRs contained in a cluster.

Sa (A $\Rightarrow$ B) = P(A $\cup B$) $*$ $(totalsamplesize)$ $*$ $(numberofTMRsofthecluster)^{-1}$

A rule was considered as linked with a cluster if S $\geq$ Sm, C=1 and Sa $\geq$ 0.5. An Sa of 0.5 meant that 50% of individuals in the cluster should contain the rule. For each cluster, the four longest rules were represented and compared to MCA and AHC descriptions. In addition, the data-mining also describes clusters' similarity and homogeneity, as these increase with number and length of rules. The combined MCA, AHC and data-mining analysis led to a complete description of TMRs for each cluster. These typical TMRs were finally compared to the most representative individual of each cluster, called the paragon, obtained in the clustering phase, to assess in what extend they match with actually existing TMRs. The statistical analyses were performed with the R software (R Core Team, 2019). MCA and data-mining were computed using the FactoMineR (Husson et al., 2020) and Arules (Hornik et al., 2005) packages, respectively.

2.2.7 Identifying farm types associated to each cluster

This final step consisted in confronting the typical TMRs to farm structural information, in order to qualitatively link the respective TMRs and their potential environmental impact to farm-level characteristics. A contingency table of plots and farm types was obtained, by cross-tabulating the TMRs of each cluster with the characteristics of the farms with which they were associated. The structural data of farms were used to classify them regarding ten criteria, representing farm characteristics, typical of the case-study-site (Poussin et al., 2008; Azizi et al., 2017). These pertained to i) access to water ("individual drilling", "collective

network"), ii) access to land ("direct access" for land owners, 'indirect access" for tenants, "indirect indirect access" for tenants who also owned some land), and iii) types of production ("grain farming", "cucurbitaceae", "leguminous", "arboriculture" and "livestock).

2.3 Results

Results, organized in five sections, first present the various TOs (Technical Operations) found in the study region, then describe the statistical analyses for each specific phase. Stemming from this step-by-step depiction, the overall characteristics of the TMRs (Technical Management Routes) are then presented. Finally, these are analyzed in the light of associated structural farm characteristics.

2.3.1 Technical operations used for statistical analysis

Six TMR steps were identified, constituted of one to eight TOs (variables) each (Table 2.2), resulting in a total of nineteen TOs. Variety type and crop spatial distribution were the strategical choices of the farmer. Tillage, irrigation, pest management, fertilization and harvesting were tactical and operational choices. As far as soil preparation is concerned, farmers had the same practice of ploughing and leveling. Two choices for the varieties were possible, with on the one hand local varieties of chili-pepper, enabling seed reuse, purchased from a nursery or grown on-farm; and on the other hand, hybrid varieties exclusively purchased, yearly, from professional nurseries. In addition, different strategies of planting date and spatial arrangements were observed. Chili-pepper could be associated to leguminous, watermelon or melon and olive groves. Data concerning overall water consumption, unavailable, were not taken into account. Two irrigation strategies were however observed, with the use – or not – of water stress periods, ranging from 10 to 30 days, which « allow good root development », according to farmers. Farmers have access to a wide range of plant protection products, applied on the basis of trade names rather than active substances. As far as fertilization is concerned, nutrient supply was mainly by fertigation. Foliar and soil applications were also common, depending on the strategies and product. Further, the harvest was very dependent on workforce and sale prices. The latter determined the dates and color of fruit at harvest.

2.3.2 MCA and clustering

The MCA was performed on 45 TMRs, described by the 19 TOs. The total inertia was 1.947, the two first factorial maps explained 41% of total inertia. Results were interpreted on the first two factorial maps.

Table 2.2: Technical operations (TO), and their defined modalities, used for the MCA and next steps of the study. Each TO has two to four modalities. NOFA = No Organic Fertilizer Application, SAP = Soil Application before Planting, SAPF = Soil Application before Planting and Fertigation, SAPP= Soil Application before Ploughing and Planting. Early planting = before April; in-season planting = from April to May; off-season planting = from June to August. * less than 15 days after planting; ** more than 15 days after planting. NA: No answer

TMR steps	TO	Modality 1	Modality 2	Modality 3	Modality 4
Tillage	Weeding/Hoeing	Early*	Late**	No tillage	
Variety choices and crop spatial distribution	Variety	Hybrid	Local		
	Planting strategy	Early planting	Season planting	Off-season planting	Regrowth
	Association with leguminous	No Association	Relay		
	Association with trees	No tree	Extensive density	Intensive density	
	Association with cucurbitaceae	Yes	No		
Irrigation	Water stress	Yes	No		
Pest management	Number of pesticide applications	0	[1,4]	(4,8]	> 8
Fertilization	Organic fertilization mode	NOFA	SAP	SAPF	SAPP
	N (kg.ha-1)	(0,50]	(50,100]	(100,150]	(150 - 300]
	P (kg.ha-1)	0	(0,60]	(60,120]	(120 - 200]
	K (kg.ha-1)	0	(0,20]	(20,40]	(40 – 100]
	Ca (kg.ha-1)	0	(0,20]	> 20	
	Mg (kg.ha-1)	0	(0,5]	(5,20]	
	Ternary fertilizer leaf application	Yes	No		
	Synthetic bio-stimulant use	Yes	No		
Harvesting	Harvest regularity	Continue	Stepped		
	Crop residue management	NA or late return	Early return	grazing and restitution	
	Crop color harvest	Green	Red	Green and Red	

Table 2.3: Cluster description. Modalities very significantly and significantly linked to the cluster are set in bold and italic, respectively. NOFA = No Organic Fertilizer Application, SAP = Soil Application before Planting, SAPF = Soil Application before Planting and Fertigation. Total rating: < 2: low; [2, 6[: neutral; [6, 10[: moderate; > 10: high.

Cluster name	Cluster (axes of interpretation)	Modality linked	Number of individuals	Total rating
Chemical input intensive and pesticide driven	1 (1-2-4)	**Hybrid variety, >8 pesticide applications, 100-150** $kgN.ha^{-1}$**, off-season planting strategies, early weeding, use of synthetic bio-stimulant, no water stress, green fruit harvest.**	7	-1
Chemical input intensive and N driven	2 (1-3-4)	**5-8 pesticide applications, 150-300** $kgN.ha^{-1}$**, 5-20** *kgMg.ha*$^{-1}$*, green fruit harvest, off-season planting.*	3	-2
Intermediary strategies	3 (1-3)	*Red and green fruit harvest,* No tree association, *<20* $kgCa.ha^{-1}$*, SAP.*	9	2
N and P driven	4 (4)	*150-300* $kgN.ha^{-1}$*, 120-200 kgP.ha-1, red fruit harvest.*	7	3
Moderate strategies	5 (2)	**SAPF, 1 - 60** $kgP.ha^{-1}$**, association with cucurbitaceae, season planting, water stress application**, *1 to 4 pesticide application, 50-100* $kgN.ha^{-1}$*, < 20* $kgK.ha^{-1}$*.*	8	9
Very low chemical input strategies	6 (1-3-4)	**Local varieties, no pesticide application, no use of K, no use of Ca, no use of Mg, no use bio-stimulant, < 50** $kgN.ha^{-1}$**, red fruit harvest.**	9	7
Regrowth strategies	7 (1-2-3)	**No pesticide application, no use of P**, *no tillage, regrowth, NOFA.*	2	8

The two first axes (Fig 2.3(a)) opposed intensive treatment and fertilization strategies, which can be described as conventional, with more moderate strategies. The former was closely linked to the use of hybrid varieties, high levels of fertilization and phytosanitary treatment on the left-hand side. On the right-hand side, axis 1 is linked to the use of local varieties and much more moderate input use. It also highlights weed control strategies, off-season planting strategies, or preferable fruit color at harvest. The absence of organic fertilization at the beginning of the cycle is expressed on axis 2. Axes 3 and 4 (Fig 2.3 (b)) express the use of ternary fertilizers and the integration of leguminous in the association. They are also associated with medium to high phytosanitary treatment modalities and the highest chemical nitrogen inputs. In addition, axis 4 reflects to some extent early planting strategies, and the harvesting of both red and green fruits.

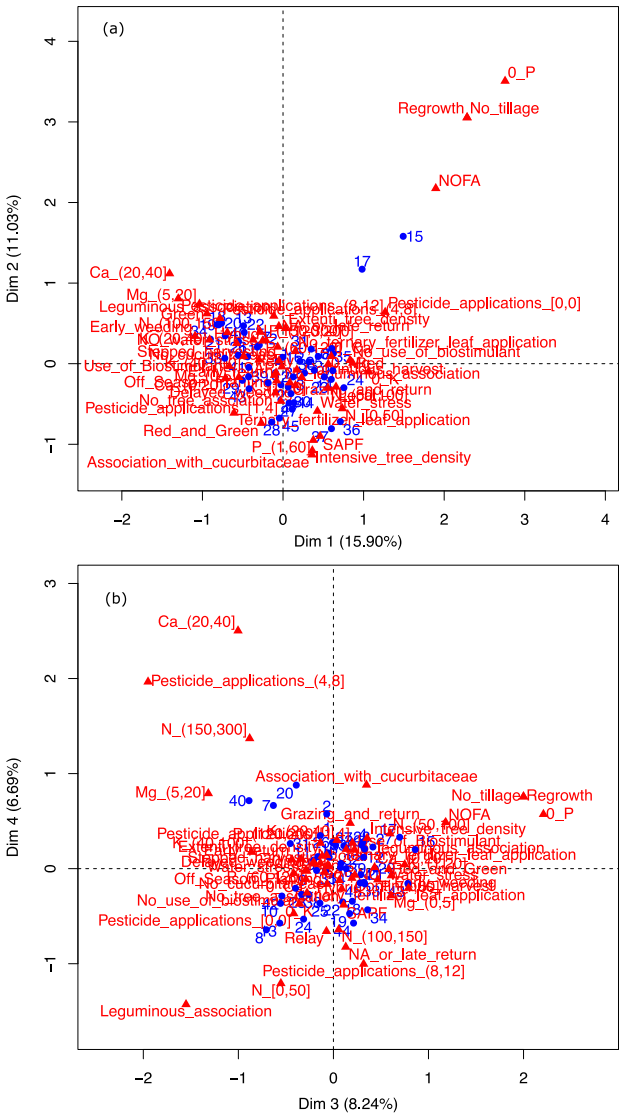


Figure 2.3: MCA Plot of individuals and variables (TOs) modalities

The AHC, resulting in seven clusters was carried out on the coordinates of the individuals on the four dimensions of the MCA and explained 66% of total variability (Figure 2.4). Fifteen variables contributed to the classification, consisting essentially in: planting strategies, number of pesticide applications, weeding/hoeing, harvest regularity, N, P, K, Ca, and Mg quantities, organic fertigation method, choice of variety, application or not of water stress, association with trees, association with cucurbitaceae, and use of bio-stimulant. The MCA coupled with the AHC results (Table 2.3) showed an opposition between conventional and chemical input intensive TMRs generally applied to hybrid varieties (cluster 1 and 2) and organic and moderate TMRs associated with local pepper varieties (cluster 5 and 6). Clusters 3 and 4 could be assimilated to mixed strategies at an intermediary position between the systems of clusters 1 and 2 on the one hand, and the moderate and low-input systems of clusters 5 and 6 on the other hand. Indeed, cluster 3 contains strategies not driven by pesticide use and N inputs, potentially applied to hybrid varieties. N and P driven TMRs are present in cluster 4, potentially applied to local varieties.

2.3.3 Association rules and cluster

The objective of data mining, which generated the association rules, was to identify additional TOs linked to TMRs and not identified at previous steps, and to assess cluster homogeneity. Minimum support Sm was set to 0.044. The results showed that the TMRs in clusters 3, 4 and 5 were much less homogeneous than clusters 1, 2, 7 and to some extent 6. Indeed, Fig. 2.5 shows a larger number of rules for clusters 1, 2, 7. Conversely, clusters 3 to 5 had a low number of associations. This is supported by the maximum length of rules for clusters 3, 4 and 5, which was lower compared to the other clusters. In other words, out of the 19 operations defining a TMR, there are in cluster 5, for instance, a maximum of 7 TOs common to at least half of the TMRs constituting this cluster, compared to 13 for cluster 1 and 10 for cluster 6. Additional TOs were identified through this process. These are included in the complete description of clusters presented in the following section.

2.3.4 Description of the seven clusters of TMRs

Figure 2.6 integrates the overall analysis of the results of MCA, ACH and datamining, and shows the most representative TMR of each cluster. It shows the TOs linked to each cluster, used to compute the rating of the degree of agroecology (Table 2.3).

Cluster 1, constituted of rather homogeneous individuals, described a TMR using hybrid varieties, intensive in terms of pesticide applications but moderate in terms of chemical nitrogen fertilization (100 – 150 kg $N.ha^{-1}$). Planting is done

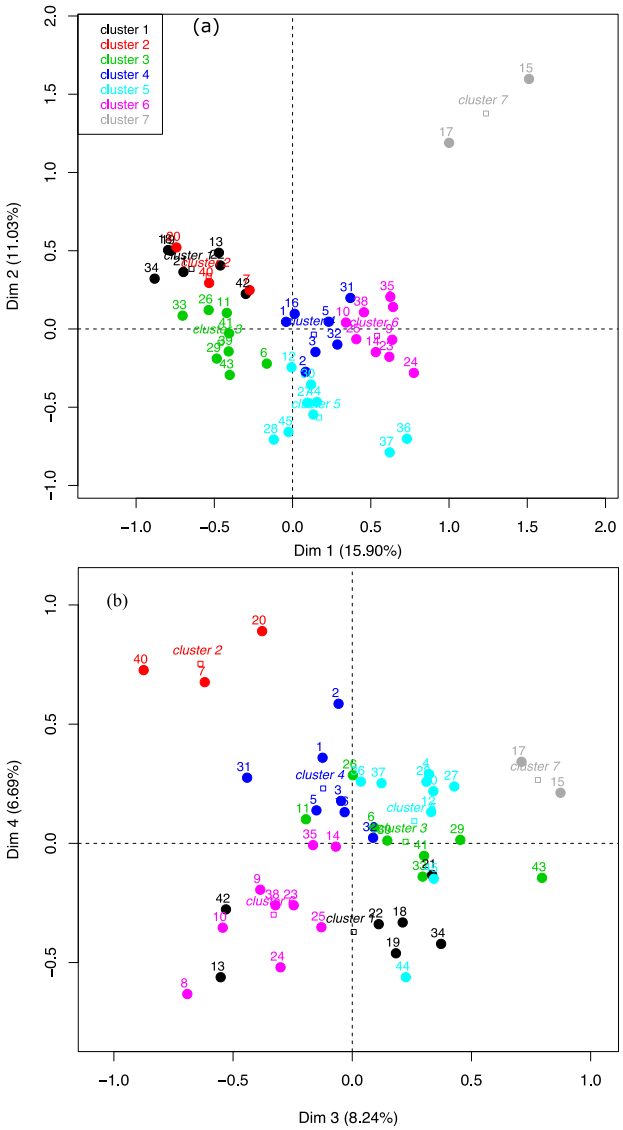


Figure 2.4: MCA Plot of individuals and variables (TOs) modalities

off-season (July-August), with an early weeding. For this TMR, there is no water stress period in the irrigation calendar, harvesting is often done when the fruits are green. In addition, this cluster is characterized by the use of synthetic bio-stimulants and a late return of crop residues. The cluster 1 had a high potential impact (low level of agroecology with total rating inferior to 2) so, these TMRs are considered as non-environmental-friendly.

Cluster 2, equally homogeneous in nature, consisted in more intensive TMRs with regard to chemical nitrogen fertilization, but moderate in terms of pesticide application. It was characterized by off-season plantation and green fruit harvesting. Further, this cluster had a high potential environmental impact, thus these TMRs are considered as non-environmental-friendly.

Cluster 3 was characterized by chili-pepper cultivation non associated to

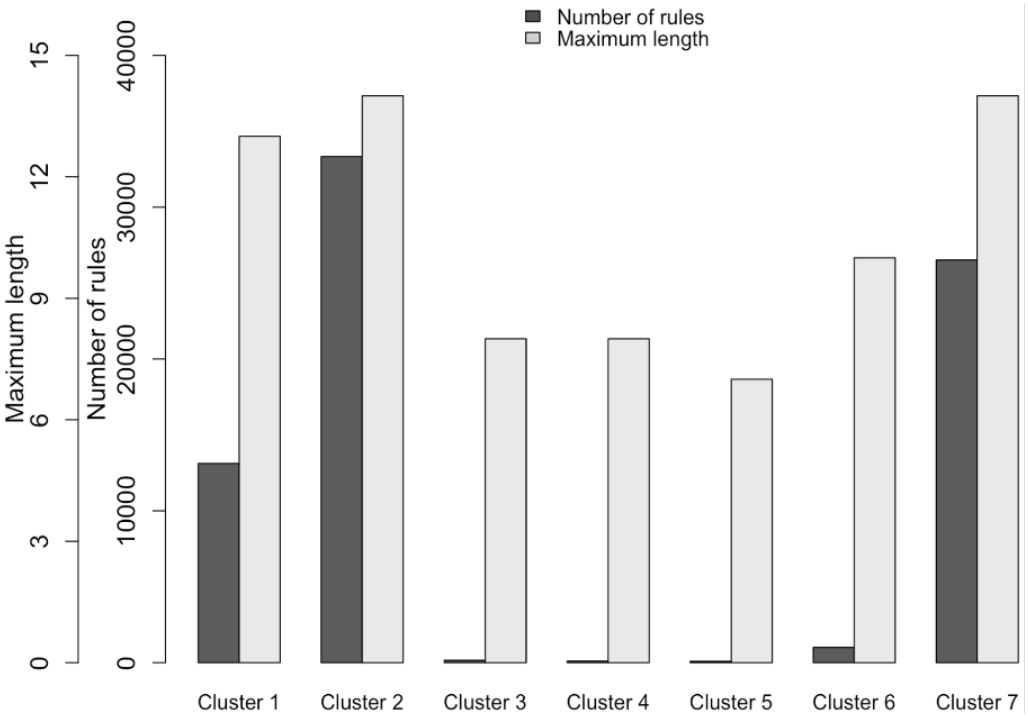


Figure 2.5: Number of rules for each cluster and maximum length of rules in clusters.

trees, the use of bio-stimulant, the application of organic fertilizers before planting and the harvest of both red and green fruits. These TMRs were mostly associated with hybrid varieties with a relatively low number of treatments (one to four treatments). They were also characterized by significant Ca and Mg inputs. Cluster 3 was very heterogeneous, particularly with regard to nitrogen fertilization, and is the only cluster not linked to any modality of this variable. This cluster had a neutral potential impact mining that these TMRs are intermediary between non-environmental-friendly and environmental-friendly TMRs.

Cluster 4 was characterized by very high chemical fertilizer inputs (150 - 300 $kgN.ha^{-1}$; 120 - 200 $kgP.ha^{-1}$, 40 - 100 $kgK.ha^{-1}$), and red-fruit harvesting. These TMRs were applied mainly to local varieties with a neutral potential environmental impact. Thus, the TMRs in this cluster are intermediary on the aforementioned agroecological scale.

Cluster 5 described systems with moderate inputs, characterized by the supply of organic fertilizers by fertigation relatively low nitrogen chemical fertilizer inputs (50-100 $kgN.ha^{-1}$) and a relatively low number of pesticide applications (<4). This cluster essentially corresponded to TMRs involved in local varieties planted in April-May. These almost always i) comprised periods of water stress in the irrigation schedule, and ii) included association of chili-pepper with cucurbitaceae. The TMRs in cluster 5 are moderately environmental-friendly as this cluster had a medium high total rating.

The TMRs in cluster 6 were very moderate in terms of chemical inputs, with no use of calcium, magnesium, potassium, nor bio-stimulant fertilizers. Chemical nitrogen inputs were very low (< 50 $kgN.ha^{-1}$), and no application of pesticides was observed. However, phosphorus inputs were high (120-200 $kgP.ha^{-1}$). These TMRs were applied to local varieties with no pest management. Fruits were harvested red. They are moderately environmental-friendly.

Cluster 7 presented an atypical farming practice. Indeed, it described management routes that were part of a two-season growing cycle, during which the residues of the first growth season were cut to initiate a second cycle by regrowth. This cluster 7 which described the second cycle, was characterized by rare interventions of the farmer, with no hoeing nor application of bottom manure at the beginning of the growth cycle. It was also characterized by a total absence of pest management. This cluster included only two individuals and is also considered as moderately environmental-friendly.

This thorough description highlights that at the territorial scale, farming practices were very diversified and contrasted. TMRs of cluster 3 and 7 were less common in the dataset. These TMRs contained very particular TOs probably rare at the territorial scale. Note that there was a wide range of alternatives to TMRs of cluster 1 and 2.

Further investigation of the potential environmental impact of the TMRs of each cluster suggests that despite this contrast, not one cluster can be seen as environmentally-friendly regarding all aspects of the TOs. Indeed, almost all the clusters were all a combination of of (non)-agroecology-compatible TOs (Fig. 2.6 (b)), even though some were more moderate than others. For instance, as far as chemical fertilization is concerned, farmers commonly applied high amounts of at least one N, P or K fertilizer. At the same time, all the clusters from 1 to 5 were characterized by the use of organic fertilizers, which is an additional supply of fertilizer. Such behavior may be explained by the fact that in most cases, farmers tend to attribute a specific role to each type of fertilizer, then, the amounts applied are defined independently. Further, despite the non-environmental-friendly characters of clusters 1 and 2, they also included some agroecology-compatible TOs. The most frequent, olive grove agroforestry, which offers increased economic benefits, is often undertaken on rented land. This suggests that some farm structural information, such as land tenure, could be linked to specific TMRs.

2.3.5 Identifying farm types associated to each TMR

This section describes the key farm structural indicators linkable to each cluster. With the strong presence of arboriculture in the region and within the sample,

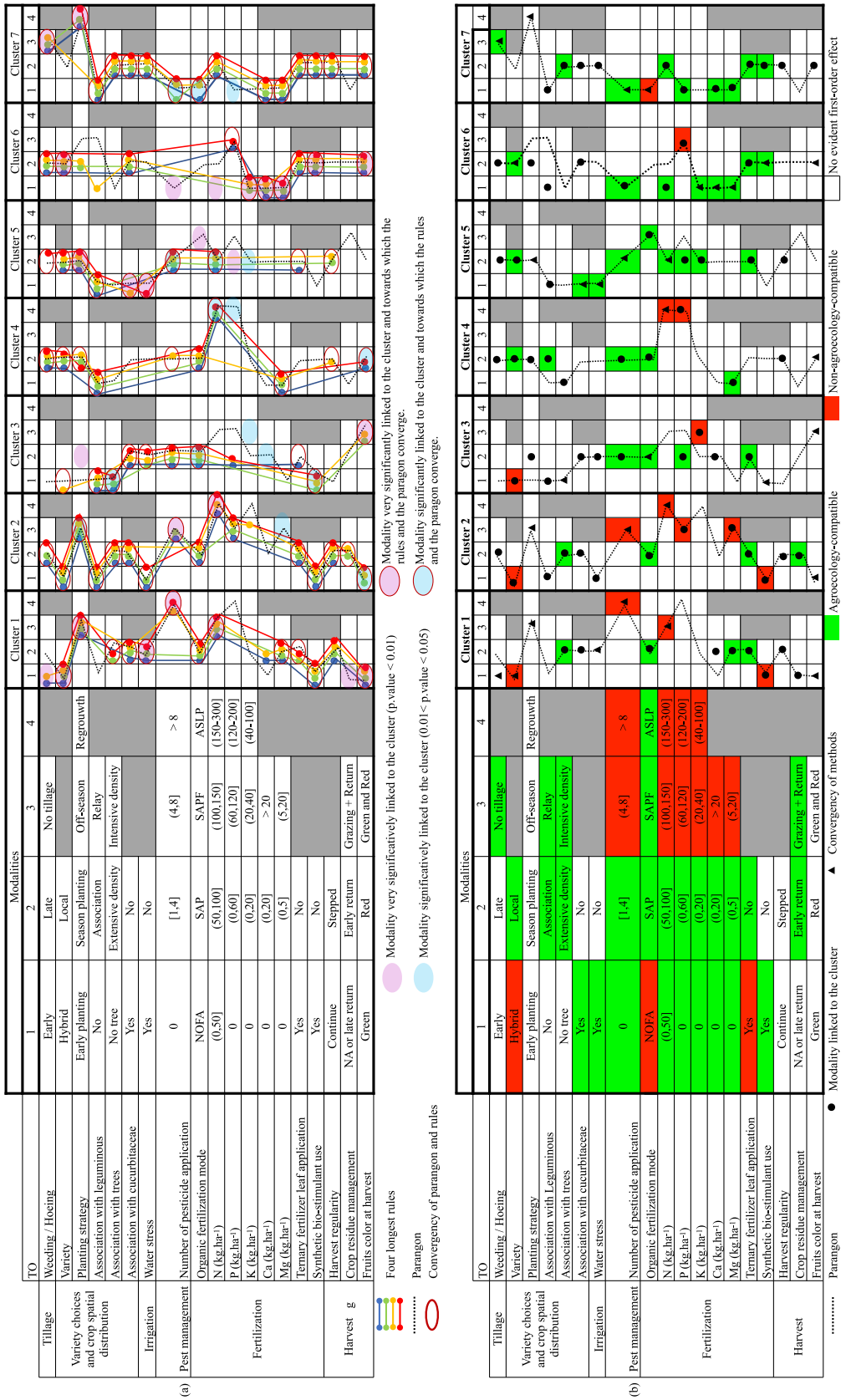


Figure 2.6: Description of TMRs. (a) TOs linked to each cluster according to the three MCA, AHC and data-mining steps. (b) Schematic representation of the same results, hightling the potentially agroecological TOs according to literature

Table 2.4: Plots and characteristics of farms: for each cluster, percentage of plots located in farms having each criterion. UAA: useful agricultural area.

Cluster	1	2	3	4	5	6	7
Sample size	7	3	9	7	8	9	2
UAA (ha)	27.4 25.1	51.3 14.1	29.3 19	15.9 8.5	12.8 11.8	10.3 10.1	17.3 20.9
Access to water							
Individual drilling (%)	86	100	78	71	75	22	50
Collective network (%)	14	0	22	29	25	78	50
Access to land							
Direct (%)	0	0	33	29	38	22	0
Indirect (%)	29	0	11	29	38	33.0	
Direct and indirect (%)	71	100	56	43	25	44	100
Production							
Grain farming (%)	71	67	100	86	75	56	50
Cucurbitaceae (%)	100	100	67	86	100	78	100
Arboriculture (%)	85.71	100	100	100	87.5	89	100
Leguminous (%)	43	0	11.11	43	25	78	50
Livestock (%)	57	0	33	71	75	78	100

Table 4 shows that this criterion characterizes the majority of farmers of all clusters. The same is true for grain farming and market garden crops in general. In addition, Table 2.4 distinguishes farms rather involved in environmental-friendly TMRs and those implementing non-environmental-friendly TMRs. Indeed, tenant farmers, oriented towards arboriculture, and vegetable crops of high added value, in particular cucurbitaceae (watermelon and/or melon), which consume a lot of water, were typically associated with non-environmental-friendly TMRs of clusters 1 and 2.

Due to high water needs, their access to water is almost exclusively through individual drilling. The farmers in these two groups seek maximum productivity and therefore tend to invest heavily in inputs, plant protection products and even land. They generally owned a piece of land to which rented plots were added. Consequently, their Useful Agricultural Area (UAA) might be relatively high, compared to other clusters. Since plot renting is often of short duration (1-2 years), they often do not have a long-term land management plan. This is rather the responsibility of the owner. However, tenants pay particular attention to crop history, and generally rent plots that have not been used in the previous crop year. Land owners ("direct access" category) generally adopted TMRs of cluster 3, 4, 5, or 6. They paid special attention to crop rotation. Thus, they were often very diversified in terms of crop cultivation. In most of cases, non-environmental-friendly TMRs (clusters 1 and 2) have relatively low UAA.

In addition, TMRs of cluster 6 were more likely associated to farms connected to a collective water network, that further cultivate leguminous or cucurbitaceae associated with livestock. Thus, it might possible to identify farmers adopting TMRs of cluster 6.

To sum up, a (non-)environmental-friendly field might be identified, regarding its farmer's type of access to land. If all or most of the lands are rented and farmer has a large investment capacity, the latter might tend to have a behavior of cluster 1 and 2. If the farmer is a land owner, diversified in production, connected to a collective network with a relatively small UAA, he might have a behavior of cluster 6. It seems more complex to find a typical farm for the clusters 3, 4, 5 and 7, taken individually.

2.3.6 Discussion

This study set out with the aim of thoroughly describing farming practices in a semi-arid Mediterranean irrigated area under multiple constraints, hypothesizing that i) these constraints lead to a diversity of farming strategies and, ii) within this diversity, some interesting environmental-friendly technical management rules (TMRs) adapted to these conditions could emerge. After presenting the advantages and limits of the methodology, the results are discussed relative to these aspects.

The methodology employed allowed to describe the diversity of farming practices among a diversity of farms, and we were able to identify some typical farm characteristics linked to some farming practices. The method we used to obtain these results is robust. The statistical tools used were indeed complementary and converged in most of cases. The method of typology, combining hierarchical classification and multivariate analyses, showed the main characteristics of the clusters. The data-mining completed the analysis by highlighting additional TOs (Technical Operations) linked to them and their homogeneity. The points of non-convergence could be due to the interpretation criteria. Indeed, TOs present in less than half of the individuals in a cluster, whose weight in relation to the total sample is relatively high, and which are described as group specific TOs by the classical method, were not retained in the interpretation of the results. As these operations are present in less than 50% of the individuals in the group, they are not taken into account in the association rules. Clusters 2 and 7 must be interpreted with caution because of their small size. A limit of the method is the long time required to do interviews. Another important point is that in the North African context, it is difficult to obtain reliable information on certain variables (yield, irrigation doses), in the absence of precise monitoring by the farmer.

Further, our findings support the statement that multiple TMRs can exist together in a relatively small territory, with the identification of highly contrasted clusters. It is a way to evaluate the co-existence of farming practices in an area. Our method is intended to be holistic and systemic as it integrated all the TMRs steps described by Wezel et al. (2014). Indeed, five types of management steps can be distinguished to describe a TMR: i) practices addressing crop and variety choices, crop spatial and temporal arrangements and successions; ii) tillage practices; iii) fertilization practices; iv) irrigation practices; and v) weed, pest, and disease management practices (Wezel et al., 2014)). Our method also took into account the farmer's operating logics at the farm level, and the interactions between various components of this system. These have not previously been described. Indeed, much work has been done on the diversity of farms (Bellon et al., 2001; Köbrich et al., 2003; Maton et al., 2005; Poussin et al., 2008; Blazy et al., 2009; Azizi, 2018; Ibidhi et al., 2018), but very little on the diversity of farming practices (Renaud-Gentié et al., 2014; Czyrnek-Delêtre et al., 2018). These results are based on reliable data obtained after in-depth discussions with farmers. To our knowledge, this study is the first to implement this method on annual crops, confirming its applicability in a wider context than previous studies focused on vineyard. The findings showed that none of the TMRs was thought in an agroecological perspective. Rather, these appear to be a combination of agroecology-(non)-compatible TOs, especially concerning fertilization practices and pesticide uses. Locally, one of the issues that emerges from these findings is that farmers commonly have a problem of fertilization management. Our study highlights the necessity for public policies, to encourage transition toward more environmental-friendly TMRs in opposition to the current tendency. Indeed, in general, it came out of discussion during surveys that TMRs likes those of cluster 1 and 2 are considered to be the "best" and "most productive" by the majority of farmers. The implementation of alternative practices is often due to economic reasons, as these are relatively less expensive. This supports previous findings showing that setting up market gardening (Azizi, 2018) and implementing agroecology-compatible practices ((Ameur et al., 2020) are driven by the cash flow of the farms and the cost of inputs. Thus, considering the number of tenant-like farm types (mostly powering TMRs likes those of cluster 1 and 2) is increasing since last decade based on additional land rentals and high added value crops (Azizi, 2018) , environmental-friendly TMRs may be much less prevalent in the future if no action is taken.

Furthermore, despite the high value of N inputs in clusters 1 and 2, most values observed in this study remain inferior to the optimum values presented in previous studies. Indeed, previous findings suggest that the optimum value of N fertilization to maximize the profitability of chili-pepper cultivation in drip

irrigation was 252 $kgN.ha^{-1}$ (Hartz et al., 1993) and 227 $kgN.ha^{-1}$ (Zhang et al., 2010). In contrast, the observed values for P application were largely superior to theoretical requirements, in most of cases. Indeed, the optimum amount of P application for chili-pepper was estimated at 40 $kgP.ha^{-1}$ by Emongor and Mabe, 2012. These are however to be taken with precaution, as pedoclimatic conditions also influence fertilizer requirements. It is important to bear in mind that the practices related to the moderate and low input clusters are not presented as agroecological systems *per se*. However, they contain a lot of single interesting and agroecology-compatible TOs. These results allow us to reassess the paradigm tending to associate irrigated agriculture to intensification and pollution. The findings provide further support for the hypothesis that smallholder farming in irrigated areas may allow the emergence of more environmental-friendly or agroecological farming practices. This study hence challenges research in agroecology in semi-arid irrigated landscapes in the Southern Mediterranean. It confirms the existence of a large range of agroecology-compatible practices at the plot level found by Ameur et al. (2020). Can these form a basis for conceiving locally-adapted, adoptable and more environmental-friendly and viable TMRs? The answer is not straightforward as the interactions among TOs and their relations with the farm-scale strategies are crucial to conceive such TMRs. At least, the high diversity of agroecology-compatible practices found in the region can be a basis towards a large-scale increase of resource-use efficiencies of existing TMRs. Thus, actions can be taken based of these practices to initiate the first steps of the Efficiency-Substitution-Redesign (ESR) process (Hill, 1998) of the agroecological transition. However, combining the agroecology-compatible practices found (such as agroforestry, leguminous integration, use of organic fertilizer etc., reduced pesticide use, use of local varieties, etc.) within new ecological-based TMRs might have social, economic and even agronomic costs. For instance, agroforestry might generate addition income but reduce cultivated area of green market crops. The use of homemade organic fertilizers can contribute to reduce the production costs but may require increased workload. The use of local varieties most resistant to pest attacks can also reduce production but in return, can also lead to lower yields. In addition, resource-use efficiencies highly depend on farmers' irrigation and fertilization strategies which have not been studied in detail. It thus remains to evaluate whether the design of ecological-based TMRs, based on the agroecology-compatible practices found, might be viable on these three axes through an agroecological assessment. More in-depth socio-economic, environmental and agronomic assessments of current and future TMRs, taking into account the whole production systems need to be undertaken. Furthermore, our results support those observed earlier by (de Lattre-Gasquet et al., 2017) describing some trends in favor of agroecological

uses of land in Tunisia. The findings could allow stakeholders in charge of agriculture to better focus their action to support smallholder farming through agroecology. Indeed, with such a diversity of farming practices, it is important to differentiate and adapt the support policies. The study can also contribute to a broader field of research on regional diversity of cropping practices. The article defined the key TOs related to each TMR and the types of farms implementing them. On the one hand, the regional representativity of these different chili-pepper TMRs could be more easily obtained by carrying rapid interviews on these key variables on a larger sample. On the other hand, the method could also be applied to the other major regional crops. The findings are also interesting for further research as far as previous studies of modeling or assessment of the environmental impact of the practices in the study zone, did not take into account this diversity (Pradeleix et al., 2012; Massuel et al., 2017; Jouini et al., 2018) or only partly (Pradeleix et al., 2018). Although the study evaluated neither the agronomic nor environmental performances of the TMRs, one simplistic assumption could be that the less environmental-friendly TMRs mostly linked to hybrid varieties lead to higher yields. Indeed, "hybrid varieties are far more productive than local varieties" according to farmers. This statement has been confirmed by additional investigations (Chloé Morel 2018, unpublished report; Akakpo et al., unpublished data, 2019) showing that in general, yields range from less than 12 $T.ha^{-1}$ for the chili-pepper local varieties to up to 70 $T.ha^{-1}$ for hybrid varieties. Hence, cluster 1, 2, and 3, mostly associated to hybrid varieties can be considered as most productive, generating in general, up to 70 $T.ha^{-1}$. Inversely, cluster 4, 5, 6 and 7 can be considered as much less productive, less than 12 $T.ha^{-1}$, as these clusters were basically associated to local varieties. However, a mix of (non)-environmental-friendly TMRs were applied to both varieties. So, in terms of agro-environmental performance of the TMRs, one can speculate that high productivity and low environmental impacts can be achieved in systems applying environmental-friendly TMRs to hybrid varieties. Indeed, the current study, based on interviews, could not precisely take into account the outputs of the studied systems, in particular yields. The qualitative assessment of the impact of TMRs and the addition of scores of TOs different in nature and with potentially very different types of impact on the environment are a limit of the study. To have objective and realistic conclusions, this assessment requires precise monitoring of TMRs, in particular of irrigation and fertilization strategies. The paragons are typical cases that could be studied for such a purpose.

2.4 Conclusion

Returning to the hypothesis formulated at the beginning of this study, we can state that at the territorial scale, farming practices in the Merguelil irrigated plain are very diversified. One of the most significant findings to emerge from this study is that technical management routes of chilli-pepper crop are very contrasted. In a qualitative manner, the findings enable to answer the main question of the study by stating that environmental-friendly technical management routes exist within the conventional agriculture known for this region. Yet, farmers seem to have a common problem of fertilization management and pesticide use. The study challenges research in agroecology in semi-arid irrigated landscapes. It gives a broader hypothesis for further research to reassess paradigms tending to oppose irrigated agriculture to agroecology. Further research might investigate the cumulative environmental impact of the studied TMRs, and their relationship to yield diversity. However, this poses a methodological problem, as it requires costly monitoring often difficult to implement in real and poorly gauged farming conditions.

Chapter 3

Field monitoring

This chapter describes a series of data collected in a smaller sample size to provide more in-depth assessment of the managements rules. It provides more detailed data on the diversity of practices, concerning water use, fertilization, yields and aboveground biomass production. To collect the data, a sampling and data acquisition method, different from the one used in chapter 2, but complementary, was used for data which could not be acquired through post-harvest interviews. The data were collected in uncontrolled and poorly gauged environments. Uncontrolled field data are particularly subject to uncertainties, which need to be taken into account in the interpretation. The chapter proposes a methodological approach to i) collect field data involving farmers in a small-scale family agricultural area; ii) quantify the uncertainty related to each data through error measurement and error propagation; iii) analyze farmers' fertigation strategies and resulting yields and aboveground biomass.



Figure 3.1: Examples of fertilizer application methods in the Merguellil downstream plain: (a) injection of fertilizer into the drip irrigation system, (b) application of Diammonium Phosphate, (c) injection of Ammonium Nitrate into the main irrigation pipe.

3.1 Introduction

The surveys carried out in 2018 show the probable existence of a diversity of fertigation strategies in the plain. Indeed, as shown in chapter 2, different types and amounts of fertilizers are applied by farmers. Fertilization and irrigation strategies are thought jointly as the fertilizers are mainly applied through the irrigation system (Figure 3.1). Considering each farmer designs his own management rules and based on the highly contrasted management rules identified for chili-pepper-based cropping systems, one can assume that the ways of applications of fertilizers might differ from one farmer to another. The absence of this specific information was one of the main limitations of the characterization of the diversity of practices in Chapter 2. Indeed, we were unable to collect reliable quantitative data on water use, or detailed information on the fertigation strategies during the surveys. Yet, these strategies play a key role in the resulting productivities. As presented in Chapter 1, a specific objective of the thesis was to assess the farming practices in both qualitative and quantitative manners. To realize the quantitative assessment of the impacts of the studied systems, reliable quantitative data on water and fertilizer (nitrogen) use and yields are needed. Thus, data collection (realized in 2019) was organized on a smaller sample size (eleven fields) through field monitoring. The Merguellil downstream plain is a particular environment, where the organization of agricultural activities, social rules and prescriptions can make it difficult to have access to these data. Hence, we adopted a methodological approach involving farmers and allowing to overcome a series of constraints related to real environment data collection.

This chapter aims at i) thoroughly describing the data collection methods and ii) analyzing farmers' fertigation strategies and plant responses (yields, biomass). In the following steps of the thesis (Chapter 4 and 5), these informations will enable an intercomparison through the agro-environmental assessment of the farming practices in the plain at plot scale (Chapter 4). To perform this assessment but also better explain the impact of farming practices and fertigation strategies and finally propose improvement pathways, crop management data presented in this chapter have been integrated in a coherent conceptual framework supported by the Optirrig crop model (Chapter 4 and 5). This allows to simulate a series of biophysical processes impacted by farmers' practices. The aim of this approach was to:

- facilitate the inter-comparison of farmers' practices;
- estimate variables that are difficult to measure at the plot level, such as drainage and nitrogen leaching;

- project the potential gains (in terms of water and nitrogen use and yields) through changes in fertigation management, to avoid wastage and pollution.

The implementation of a modelling approach required detailed fertigation scheduling on each field, but also knowledge of soil parameters, plant growth stages, and aboveground biomass and yields. These data were collected on each field. Although uncontrolled environments represent difficult conditions for agricultural experimentation, on-farm research was preferred for three reasons. First, it is known that there are difficulties for certain achievements and proposals of agricultural research to be adopted by farmers especially in southern countries (Philippe, 1990; Banhoro et al., 2019). Secondly, there is an important variability in farms' soil and socio-economic conditions. Third, there is no available data on the farmers' practices, reproducible in controlled environment. Furthermore, we are aware of the uncertainties related to on-farm research. It is important to determine whether potential differences in responses are due to inaccurate field measurements or related to farming practices. Hence, the error related to each type of data has been quantified.

This chapter is organized as follows. After describing the plot sampling procedure, the experimental design and the methods used to monitor fertigation and to measure yields and biomass are presented. Thereafter, the data analysis and error estimation are described. Then, the fertigation strategies are described, followed by a cross-analysis of yields and some crop management data. And finally, these results are discussed in the last part of the document.

3.2 Methodology

Data collection and the analysis of fertigation practices were organized in four steps (Figure 3.2). First, the study plots were selected based on the clusters obtained in Chapter 2, in order to characterize a wide range of diverse practices representative of the case-study site. Second, a protocol, allowing the acquisition of a large range of data from several farms, was designed. The third step consisted in identifying the sources of uncertainty and quantifying their ranges of variability. Finally, the analysis of the collected data allowed a preliminary description of fertigation practices and resulting yields.

3.2.1 Plot sampling

The sampling was carried out in order to have all the major clusters described in Chapter 2 represented. Note that, the regrowth strategies (cluster 7), which represent very specific pepper farming practices, were excluded, i) due to their

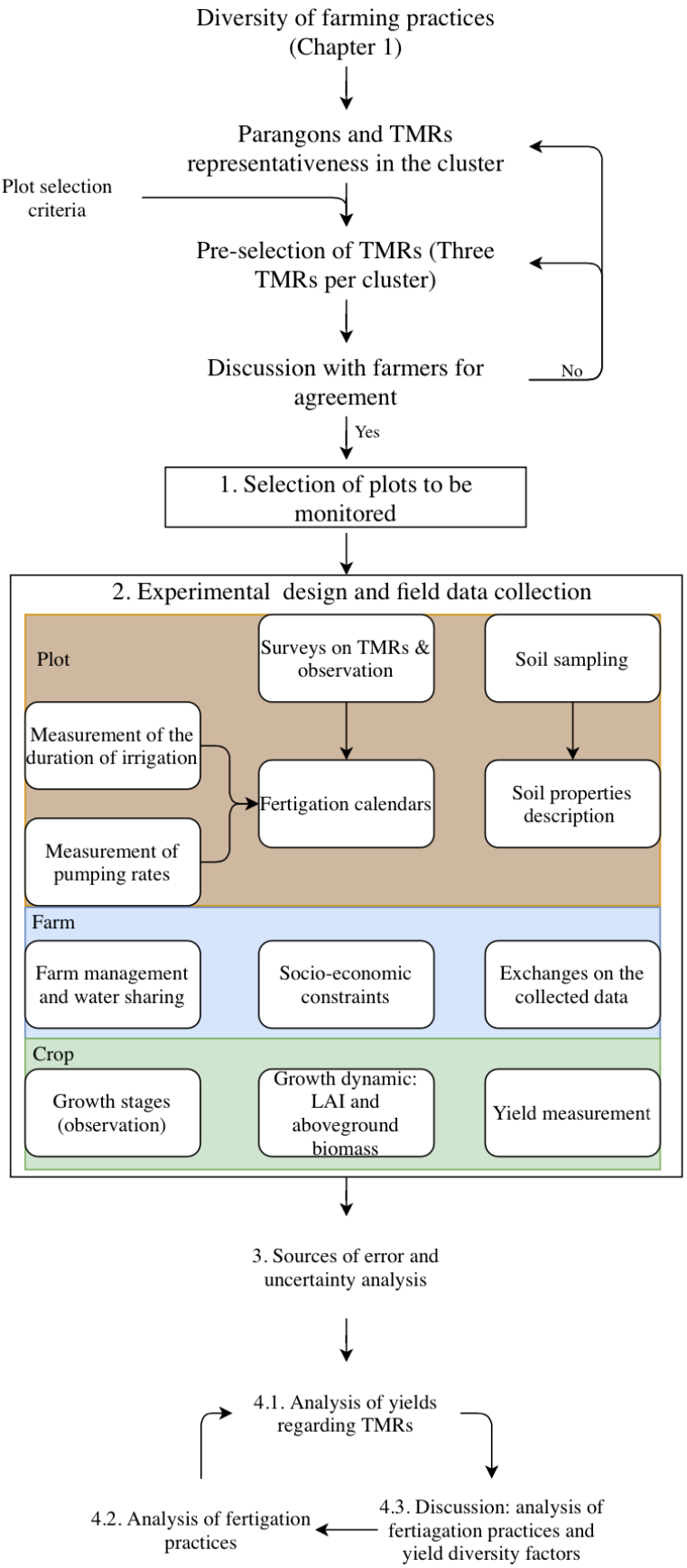


Figure 3.2: Field data collection methodological flowchart.

specificity (double cropping season) and ii) this cropping system was not identified in the case-study site in 2019. Three criteria were defined to choose the fields to be monitored and ranked in order of priority. First of all, the farmer's agreement and interest in participating in the study was necessary because of the strong farmer involvement required. The second criterion was the representativeness of the management rules in relation to the clusters (paragons). Third, farms with individual water sources were given priority, assuming that the collective networks might generate variable water flow which might increase the uncertainty in water consumption estimation, leading to a poor understanding of the fertigation-yield relationships. Furthermore, in this highly diversified environment in which only a limited number of fields could be monitored, the inclusion of fields with different varieties of chili-pepper and different soil properties were privileged over different sources of water. Fifteen plots were initially selected. The study was finally carried out on eleven of them. Indeed, two farmers finally decided to not grow chili-pepper that season and two other farmers experienced transplantation failures. Seven fields of hybrid pepper variety "sahraoui" and four of local variety "baklouti" were involved in the monitoring. Except for cluster 7, all clusters were represented at least by one field, if not two to three.

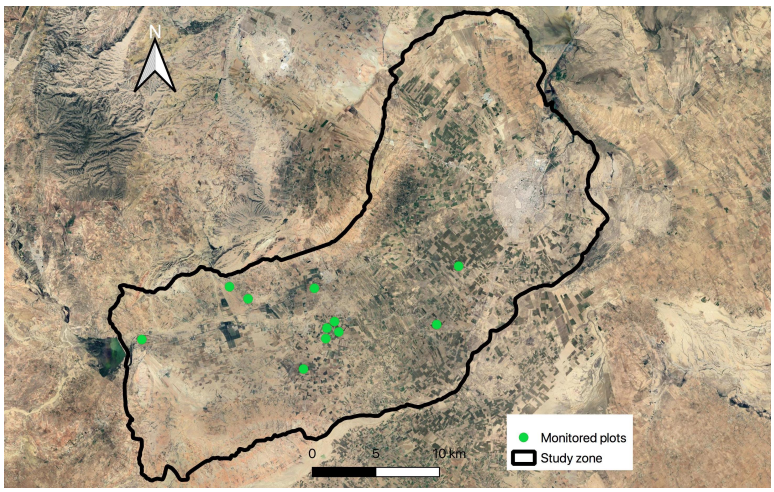


Figure 3.3: The study zone with the location of the monitored fields.

3.2.2 Experimental design: field and TMR characteristics

The study started in the spring of 2019 and ended in December 2019. Table 3.1 presents the main characteristics of the topsoil layer (0–20 cm) for each plot. The soil texture was heterogeneous with sandy and clay-sandy types. The averaged soil texture in the topsoil layer was 53.0% $\pm$ 12.9 clay, 27.7% $\pm$ 6.9 fine silt, 6.0% $\pm$ 1.9 coarse silt, 9.4% $\pm$ 11.1 fine sand and 4.8% $\pm$ 7.0 coarse sand.

Other major characteristics seem quite homogeneous: all soils are slightly alkaline, carbonated, with a low organic matter content. The management rules were entirely designed by the farmers. All the plots were independent, and no recommendations were made to farmers. As described in chapter 2, seedlings of the local chili-pepper varieties were grown on-farm; and hybrid varieties exclusively purchased from professional nurseries. Some farmers had the same provider. Fertigation was operated by the farmer, a family relative or sometimes by a laborer. The soil was prepared a few days before transplantation. P2, P5, P6, P7, and P9 received organic manure before transplantation; P2, P4, P8 and P11 about two weeks after transplantation. No organic manure was used on P1 and P10. However, P1, P2 and P5 used homemade liquid organic manure for fertigation. Further, on P4, P7 and P10, chili-pepper was cultivated in association with olive trees.

3.2.3 The monitoring of TMRs

Three data collection methods were combined to monitor the management rules on each field: on-farm interviews, phone interviews and direct observations. Each field was visited at least once a week. The on-farm interviews were realized each time a farmer was present and available. These discussions were centered on the technical operations realized during the previous days, and the projected operations of the up-coming weeks. These were not formal prepared interviews, but rather opportunities for exchange, allowing farmers to explain the way they operate, the difficulties or constraints they encountered. The questions were driven by direct observations (plant growth, soil) which play a key rule. The direct observations enabled to identify some changes or some interventions realized by the farmers. They also allowed to verify whether the interventions projected by the farmers were realized and if not, to ask why these were cancelled or postponed. The discussions also concerned the activities on the other fields of the farms. Indeed, it is quite important to analyse the monitored field in relation with all the components of the farm. Moreover, additional informations were collected by phone call. These phone call interviews were also realized if no direct interviews was done for a long period of time.

3.2.4 Monitoring of fertigation

Water consumption at plot scale is difficult to estimate, since the farms are not equipped with water-meters (except for P7). But these data are crucial to analyze fertigation practices and assess water productivity. So, water consumption was estimated through an indirect method, consisting in measuring, in a non-disturbing manner, the water pumping rate and the duration of irrigation. This indirect method allows to estimate not only water consumption, but also, the

Table 3.1: Main characteristics of the topsoil layer (0–20 cm) on each plot

	Variety	Fertigation	TMRs	Biomass	Soil properties	Soil Nitrogen	Marketable Yield	Dry Yield	FC and WP	LAI *	Root Profile	Biomass * Dynamic	Hydric Potential
P1	hybrid	X	X	X	X	X	X	X	X				
P2	hybrid	X	X	X	X	X	X	X	X				
P3	hybrid	X	X	X	X	X	X	X	X				
P4	hybrid	X	X	X	X	X	X	X	X				
P5	Local	X	X	X	X	X	X	X	X				
P6	hybrid	X	X	X	X	X	X	X	X	X	X	X	X
P7	hybrid	X	X	X	X	X	X	X	X				
P8	local	X	X	X	X	X	X	X	X				
P9	local	X	X	X	X	X	X	X	X				
P10	local	X	X	X	X	X	X	X	X				
P11	hybrid	X	X	X	X	X	X	X	X				

Table 3.2: Main characteristics of the topsoil layer (0–20 cm) on each plot

	pH	Electric conductivity	Total phosphorus	Total Potassium	Active Limestone	Total Limestone	Organic matter	Nitrogen	Corg/N	Clay	Fine silt	coarse silt	Fine sand	coarse sand
		mS/cm	Pmg/kg	Kmg/kg	%	%	%	%■	-	%	%	%	%	%
P1	8.688	0.241	1106	11643	18.5	33.98	1.49	0.65	13.37	61.7	28.4	4.9	4	0.9
P2	8.632	0.113	1150	12037	18.5	34.7	1.37	0.68	11.66	59.4	28	4.8	7.3	0.5
P3	8.387	0.171	999	11633	16.5	36.24	1.51	0.54	16.18	58.4	33.1	5.5	2.3	0.6
P4	8.387	0.171	999	11633	16.5	36.24	1.51	0.54	16.18	58.4	33.1	5.5	2.3	0.6
P5	8.962	0.15	1056	12101	13	27.59	1.59	0.53	17.56	46.9	28.8	9	12	3.3
P6	8.73	0.128	561	11775	19.7	31.94	1.22	0.64	11.09	60.4	29.9	4.1	4.8	1
P7	8.639	0.127	919	9357	8.5	22.91	1.64	0.67	14.18	25.9	12.8	8.5	33.4	19.4
P8	8.73	0.711	985	11944	20	31.94	1.22	0.64	11.09	60.4	29.9	4.1	4.8	1
P9	8.089	0.711	985	11944	20	31.94	1.22	0.64	11.09	60.4	29.9	4.1	4.8	1
P10	8.67	0.711	985	11944	20	31.94	1.22	0.64	11.09	60.4	29.9	4.1	4.8	1
P11	8.79	0.711	985	11944	20	31.94	1.22	0.64	11.09	60.4	29.9	4.1	4.8	1
Min	8.089	0.113	919	9357	8.5	22.91	1.22	0.53	11.09	25.9	12.8	4.1	2.3	0.5
Max	8.962	0.711	1150	12101	20	36.24	1.64	0.68	17.56	61.7	33.1	9	33.4	19.4
Sd	0.28	0.21	78.65	956.7	3.96	4.99	0.14	0.07	2.44	12.92	6.92	1.91	11.09	6.97

dates of irrigation, in opposition to other methods such as installing a water meter. The amount of water supplied C ($m^3.ha^{-1}$) at each irrigation episode was then the product of the pumping rate Q ($m^3.h^{-1}$) and the duration of irrigation T (h).

$$C = Q * T \tag{3.1}$$

Table 3.3: Description of the irrigation systems

	Pump capacity (hp)	Flow rate (m3/s)	Valves	Valves /Irrigation
P1	3	15.39	8	1
P2	15	23	6	3
P3	7	24.5	6	2
P4	15	27	12	3
P5	7	20.5	12	2
P6	15	20	7.5	1
P7	PPI	14.6	6	3
P8	7	23.13	5	1
P9	10	10.5	1	1
P10	5	25.25	7	1
P11	20	27.2	7	1

Therefore, the monitoring of irrigation was realized in two steps: the estimation of dates and duration of irrigation and the estimation of water pumping rates. For market gardening, the farmer usually divides his fields into several irrigation units, controlled by valves. Depending on the pumping capacity (Table 3.3), each farmer irrigated one, two, or three units at a time. It was assumed that water supplies were equivalent on every irrigation unit of a same plot. To estimate the dates and duration of irrigation, a method developed by Dewandel et al. (2007) and adapted by Massuel et al. (2009), based on temperature monitoring, was used to record irrigation duration. It is a simple, economical and easy to implement method on a group of plots. It had the advantage to be a non-invasive method, which was important for farmers. The principle is that "during irrigation, the irrigation pipe is characterized by a steady temperature value relatively close to the ground water temperature" (Massuel et al., 2009). The method consisted in recording the temperature of the main irrigation pipe leading to the irrigation unit and identifying the different stages of irrigation. One irrigation unit by field was selected randomly and was equipped with two temperature loggers. One logger was installed on the irrigation pipe, and the other one was installed on a non-connected empty pipe, measuring air temperature (Figure 3.4). The Thermochron iButtons logger (model DS1921H-F5) manufactured by Dallas Semiconductor, was used for temperature record. Its measures range from 15°C to 46°with a 0.125°C resolution. The record interval

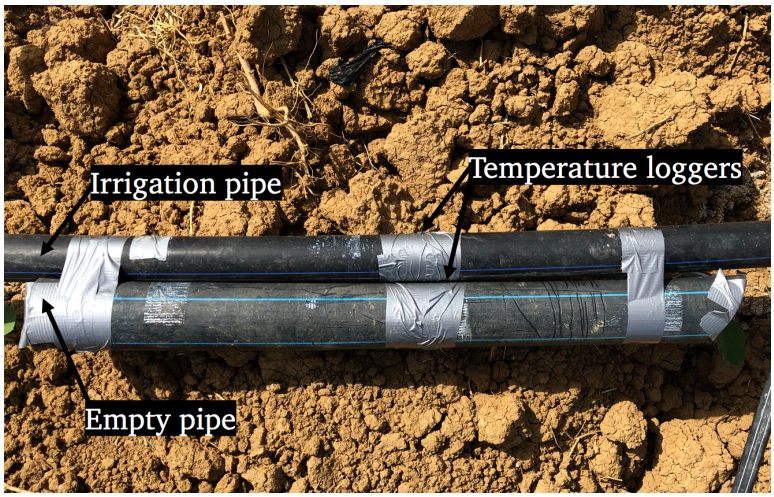


Figure 3.4: Thermochron iButton fixed on irrigation and empty pipes.

was set to five minutes, and data were collected at a one-week time period (maximum recording period based on the above settings). All fields were monitored with this system.

In the second step of the monitoring of irrigation, the pumping rate was measured on each field using an ultrasonic flowmeter. The latter, which allows the measurement of the water flow in a non-invasive manner, uses ultrasonic waves to determine the flow rate through probes (Figure 3.5). One measurement was realized on each field and was taken at the water outlet pipe of the borehole or right before the irrigation valves. Then, the flow rate of an irrigation unit was equal to the measured flow rate relative to the number of units irrigated at the time. After these two steps, water consumption at an irrigation unit was computed and consumption at the plot scale was equal to the consumption of one unit multiply by the total number of units.

In parallel to these measurements, additional informations on fertigation were collected during the surveys on management rules (section 3.2.3, page 56). These surveys allowed to complete and confirm the logger's measurements. They also made it possible to be continuously aware of the interventions performed by the farmer. Information on fertigation were collected on the field, and sometimes by phone call. All these measurements enabled to establish a thorough fertigation schedule for each field.

3.2.5 Crop data: yield, biomass, LAI and root depth

The marketable yield, which conditions the economic income, is the main variable of interest for farmers. Chili-pepper fruit harvesting started about ten to sixteen weeks after transplantation, and lasted until December and sometimes



Figure 3.5: Flowmeter probes installed on an irrigation pipe.

mid-January, with a harvest every two or three weeks approximately. The harvest was ensured by local and family labor. Farmers did not always communicate the dates of harvest in advance, as it is conditioned by manpower availability and market conditions. We were therefore unable to participate in all harvests of each field. Hence, three complementary methods were used to estimate the marketable yield (Figure 3.6). First, yields were estimated using three 25 m^2 plots, randomly installed within the plot (figure 3.6(b)). The entire fruits harvested on each 25 m^2 plot were collected and weighted. The second methods of marketable yield estimation was, to multiply the number of crates harvested by the average weight of the crates (communicated by farmers), which was about 12 kg. The third method was to directly collect the total weight of fruits harvested on the whole plot from farmers. To check the validity of these methods we compared some measurements and they consistently converged to approximately the same value. To estimate dry yield which is highly recommended to compare the performances of cropping systems, about 1kg of fruits was collected and oven-dried (63 °C for 3 days). This allowed to estimate the fruit moisture content. The total dry yield (kg) was then calculated by multiplying the marketable yield by the percentage of fruit dry matter.

Furthermore, three plants were randomly sampled after the last harvest, except for P6 and P11 (we assume no substantial changes in biomass occurred in biomass during that period of time), where two harvests occurred after the sampling. These plants were oven-dried by twenty-four hours after sampling, at 63 °C for 3 days, to estimate dry aboveground biomass production.

Further, root depth, a parameter required to run the Optirrig model, was measured. A root profile was realized on P6 (we were unable to realize this measurement in all fields) through a root count on a 5 cm grid (Figure 3.7) and



(a) (b)

(c) (d)

Figure 3.6: (a) chili-pepper plot before harvesting, (b) marketable yield measurement using 25 m^2 plots, (c) marketable yield measurement through the number of crates harvested, (d) weighting of total harvest

enabled to determine the maximal root depth to use in the modelling approach. It is assumed that maximum root depth was the same for all plots and for both hybrid and local variety. The profile was realized 73 days after transplanting.

Leaf Area Index (LAI) measurements were also required to perform the modelling. Indeed, these data enable model parameter calibration. LAI was measured on P6 using a destructive method consisting in scanning and measuring leaf area. Plants were sampled at different growth stages (10, 20, 40, 58, 73 days after transplanting). The leaves were scanned using a scanner-printer and their areas "A" (m^2) were measured using the ImageJ software (Schneider et al., 2012), as shown on Figure 3.8. We considered each plant covers an elementary soil surface equal to distance ***d*** (m) between two cropping rows times the average distance ***e*** (m) between two plant in cropping row. On P6, ***d*** was equal to 1.3 m on average and ***e*** equal to 0.2 m. For each date of measurement, the LAI ($m^2.m^{-2}$) was computed as follow:

$$LAI = \frac{1}{d * e} * A \tag{3.2}$$



Figure 3.7: Root development of chili-pepper, 73 days after transplanting.

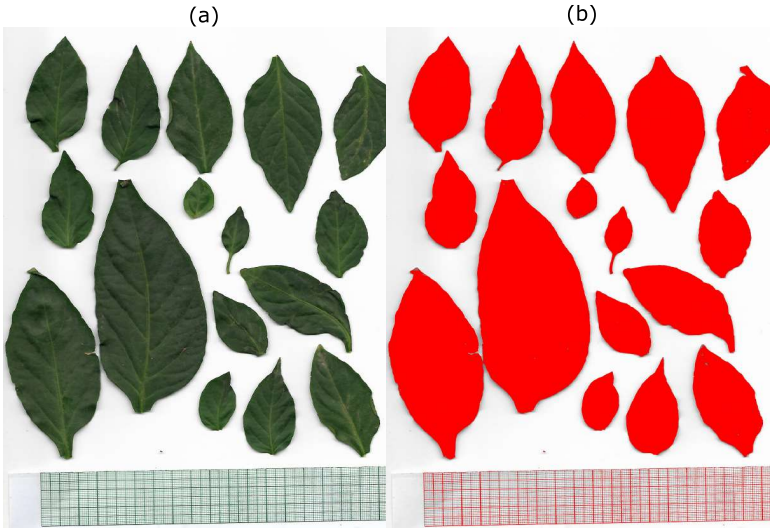
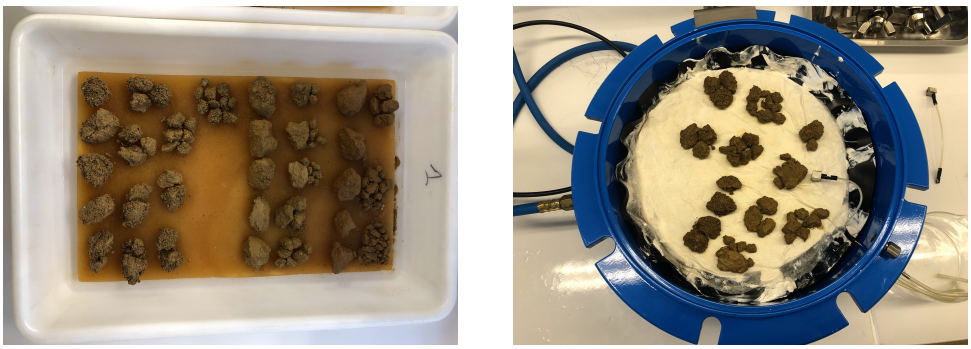


Figure 3.8: Leaf Area Index measurement (a) scanned image; (b) processed image using the ImageJ software. The graduated marker are used to set the scale of the image



(a) (b)

Figure 3.9: Field capacity and welting point measurement (a) sample saturation, (b) preparation for pressurizing

3.2.6 Soil data

Soil was sampled from each plot at planting date and at the end of harvesting. A composite sampling was done randomly at three soil depths (0-20 cm, 20-40 cm and 40-60 cm). The samples were used to realize a series of measurement including physico-chemical properties and residual nitrogen. Residual nitrogen samples were frozen after sampling. All the measurements were realized by the CIRAD soil analysis Laboratory (Montpellier, France).

The top soil samples were also used to measure the soil field capacity and (FC) and wilting point (WP). The measurement were realized at the LISAH laboratory (Montpellier). Soil aggregates were saturated for 24 to 48 hours (Figure 3.9(a)) and then put under pressure respectively at 15 bars for the wilting point and 3 bars for the field capacity. After 24 hours, samples were removed, each aggregate was weighed and oven-dried at 105°C for 24 hours. Then, dry weight was measured and the water content corresponding θ to each pressure was computed using the following relation:

$$\theta = \frac{W_w - D_w}{D_w} \tag{3.3}$$

where W_w is the wet weight of the aggregate and D_w is the dry weight. Three to six aggregates were used for each pressure and per field (sandy soils did not have enough aggregates). The water content at field capacity and welting point for each plot was then computed as the average of the water contents of each of the aggregate.

3.2.7 Data analysis, uncertainty and error propagation

Different types of data have been collected during the field monitoring. These enabled to compute a set of variables including yield ($kg.ha^{-1}$), fertigation schedule (doses and dates) and aboveground biomass ($kg.ha^{-1}$) used for the modelling and agro-environmental assessment steps. However, a series of intermediary variables were computed to get these variables of interest. The uncertainty related to each variable was estimated. The method of estimation of each variable and the related error is described on Figure 3.10. Some assumptions were made for errors that could not be directly estimated.

Model input variables: fertigation scheduling

We considered the approach used to establish irrigation schedules reliable enough to allow the detection of any irrigation. The error on the duration of one irrigation was set to 600 seconds, meaning 5 minutes absolute error on the detection of the beginning or the end of irrigation, linked to measurement frequency (5 minutes). There were some missing temperature records data due to missing or stolen loggers. These missing data were replaced by farmer-said data. These farmer-said information combined with previous irrigation habits allowed better detection of irrigation phases when the latter did not appear in the logger records. Indeed, a farmer who started irrigation approximately at the same time the last two or to three weeks, might tend to do the same the following week. Thus, farmers' indications or the average duration of irrigation of the two previous weeks were used to replace missing records. Farmer-said data are sources of uncertainty mainly the amounts of applied fertilizers. We defined three level of confidence depending on the feeling and how consistent declarations were compared to data of 2018 surveys: high, medium and low. The high level was associated to a 5% percent error, medium to 10% error and low to 15% error.

Model output variables: Yield and biomass

Yield ($kg.ha^{-1}$) and biomass ($kg.ha^{-1}$) were estimated as total dry yield and biomass relative to the cultivated area. Sources of uncertainty related to yield estimation are multiple: methods of measurements, estimation of cultivated area, farmers' information. Uncertainty related to aboveground biomass estimation mostly came from possible spacial variability in biomass and lost biomass during harvest. It was assumed the latter was negligible.

Furthermore, a discussion section is presented on the uncertainty of the collected data to analyze the importance of the uncertainties and their potential impacts on the results. Three levels of uncertainty (low, medium and high) were defined and affected to each measured variable, based on i) the sensibility of some variables to the uncertainty of another one, ii) the source of uncertainty

Categorie	Variable	Name (Type)	Unit	Formula	Error estimation
Plot characteristics	e	distance between two plants (4)	m	e± ΔE	ΔE = 0
	d	distance between two irrigation rows (4)	m	d ± ΔL	ΔL = 0
	Np	Total number of plants (1 - 2)		Np ± ΔNp	ΔNp = set to 0
	S	Cultivated area	ha	S ± ΔS	ΔS = sd(Measured S, farmer S)
Irrigation	D	Crop density (4)	plant/m2	1/(d*e) ± ΔD	ΔD =0
	Date I	Date of irrigation (I)	-	-	0
	ti	Duration of irrigation (2)	s	ti ± Δti	Δti = 600
	Q	Pumping flow (2)	m3/s	Q ± ΔQ	ΔQ Estimated per plot
	n	Number of elementery irrigated areas (2)	-	n	0
	I	Amount of water applied / irrigation (1)	mm	Q * t * n * 1000 / S_c * 10000 ± ΔI	ΔI = I * ((Δt/t) + (ΔQ/Q) + (ΔS_c/S_c))
	Date N	Date of N application (1)	-	-	-
Fertilization	p	% N in the fertlizer (2)	%	p	0
	F	Amount of applied fertilizer (2)	kg	F ± ΔF	ΔF = farmer-related incertainty"
	Dose N	Amount of Nitrogen/application (1)	kg	F * p * n / S + ε1 ± ΔN	ΔN =N * (ΔF/F + ΔS/S + deltaε1/ε1)
Yield	c	Number of fruit crates harvested (4)	-	c ± Δc	Δc unknown
	Pc	Weight of a crate (4)	kg	Pc ± ΔPc	ΔPc estimated per plot
	P	Total Fruits weight (4)	kg	c * Pc ± ΔP	ΔP = P(Δc/c + ΔP/P)
	Yw	Marketable yield	kg/ha	P/S_c ± ΔYw	ΔYw = (P/S) * (ΔP/P + ΔS_c/S_c)
	θ	fruit water content (4)	%	θ ± Δθ	Δθ estimated per plot
	Y	Dry yield (3)	kg	θ * Yw ± ΔY	ΔY = Y(Δθ/θ + ΔYw/Yw)
	b	Plant above ground biomass (4)	kg	b ± Δb	Δb = estimated + ε = unknwon
	B	Total above ground biomass (4)	kg/ha	b * 10000*D ± ΔB	ΔB =B * (Δb/b + ΔD/D)
	TDM	Total dry matter (3)	kg	TDM = B + Y ± ΔTDM	ΔTDM = ΔB ± ε2 + ΔY
	A	Leaf surface (4)	m2	A ± ΔA	ΔA Unknown
	LAI	Leaf Area Index (3)	m2/m2	A / (e * d) ± ΔLAI	ΔLAI = LAI * (ΔA/A)

Figure 3.10: Variables calculation and uncertainty estimation. The green rows represent model input variables (intermediary variables in light green; blue rows are model outputs (with intermediary variables in sky blue

and iii) the accuracy of the measurements. The aim of this was to appreciate whether uncertainty was high or not, which data had the highest or lowest uncertainty, which results were more accurate and which might be taken with reserve.

The collected data enabled to generate the cropping calendar for each plot. To analyze farmers' fertigation strategies and plant responses, the total amounts of water and nitrogen supplied on all fields were compared. The related global fertigation strategies were analyzed by identifying the key stages of irrigation and fertilization at a daily time frame. Then the aboveground biomass, marketable yield and dry yield were compared at both plant and plot scale. Next, we performed a primarily analysis of yield regarding management practices. The irrigation and fertilization schedules, soil properties and the aboveground biomass production and leaf area index dynamic are mobilized in Chapter 4, to model the crop evapotranspiration, water drainage and nitrogen leaching.

3.3 Results: analysis of fertigation strategies and diversity of aboveground biomass and yields

3.3.1 The cropping calendars

Figure 3.11 presents the cropping calendar on each field showing the periods of realization of technical operations. In general, soil preparation was done a couple of days before the transplantation. The earlier plots were installed in April, while the latest were installed in July. The date of transplantation depends on whether the farmer wanted to produce earlier season, season or off-season chilli-pepper fruits. The transplantation lasted two to five days depending on field size and manpower. Irrigation started on the day of transplantation, and was realized either at same moment or a few hours before. The end of irrigation depended on farmers' strategy. In some case, the plants could be irrigated till the last harvest (P10 for instance). The fertilizers were applied at different moments during the cropping cycle. Harvest started minimum two months and half for the hybrid variety, and about three months and half for the local variety. The duration between the first and the last harvest depended on the date of transplantation and ranged from two months to more than five months.

3.3.2 Duration of irrigation and irrigation schedules

Recording irrigation pipes and air temperature allowed to detect irrigation phases, since air and water temperature were highly contrasted. The average groundwater temperature was about 22 °C. Depending on the irrigation occurrence, it ranged from 22 to 30°C (during the summer). Indeed, the boreholes were

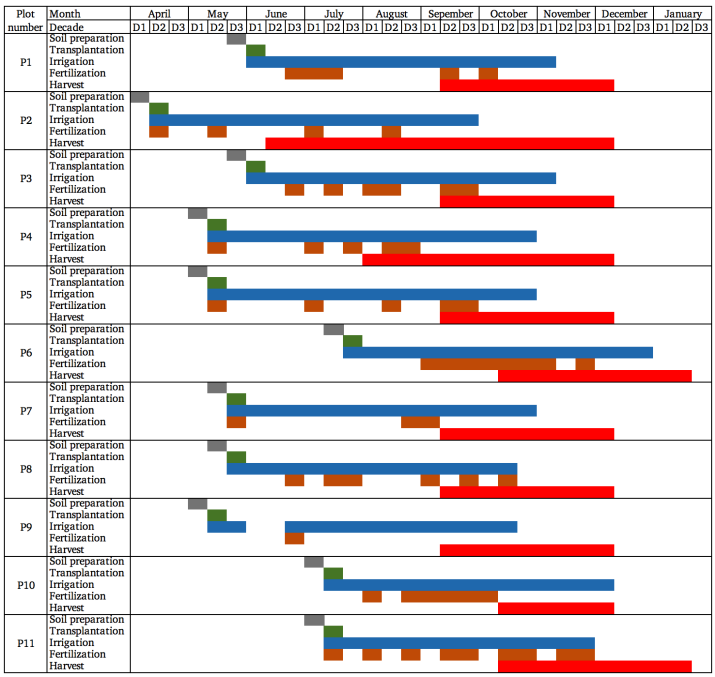


Figure 3.11: Cropping calendar for each field, presenting the decade of soil preparation and transplantation, the key periods of fertilization, irrigation and harvest.

sometimes about 1500m far from the fields, and transport was operated with unburied pipes causing higher temperature of water in irrigation phases especially during the summer.

Figure 3.12 is an example of detection of irrigation phase (overlaid in grey), confirmed by the farmer showing a plateau in records. In some cases, detection was more complex (see Figure 3.13). For example, it can be more complicated to detect the right starting or ending point when air temperature was close to the groundwater temperature. These situations mostly occurred when irrigation was realized at night. Discussions with farmers were particularly useful in these cases to confirm the detection. Figure 3.14 shows an example of temperature recorded with missing data for air temperature (in this case, the logger was stolen). Thus, air temperature was replaced by the average air temperature of all the other fields. Further, fluctuations could be observed between air and pipe temperature during non-irrigation phases or "fake" plateaus could be observed (Figure 3.14). This made complex an automatic detection of irrigation phases. Hence, the later was thus done manually, which is time consuming but more accurate.

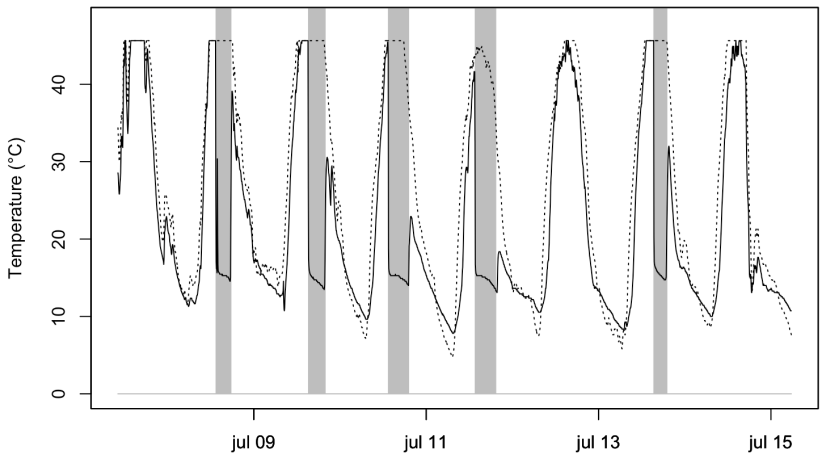


Figure 3.12: Example of temperature time series recorded one field. The black line is the irrigation pipe temperature and the doted line is the air temperature. The records show temperature plateau occurring when water flows into the irrigation pipe. The detected irrigation phases are overlaid in grey.

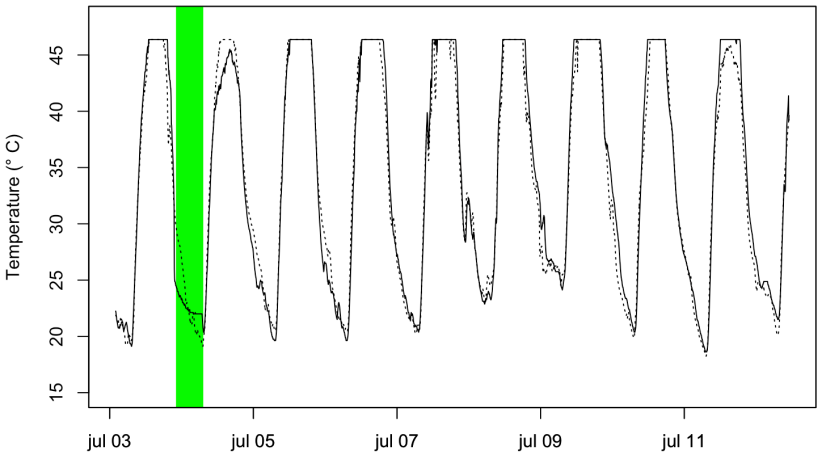


Figure 3.13: Example of temperature time series recorded where the detection of irrigation phase was trickier. The black line is the irrigation pipe temperature and the dotted line is the air temperature. The irrigation phases are overlaid in green was not detected but confirmed by the farmer.

3.3.3 Fertigation strategies

Several water-soluble fertilizers like N-P-K (20-20-20, 13-40-13), ammonium nitrate, calcium nitrate and magnesium nitrate, etc., were used by farmers for fertigation. Diammonium Phosphate (DAP) was commonly used as an additional source of nitrogen, applied as a basal dose of fertilizer before transplanting or right after. The amounts of organic nitrogen (organic manure or homemade liquid organic fertilizer), were not taken into account in the analysis, since it was not possible to quantify them. Nutrients such as K, P, Ca, and Mg, that play an essential role in plant growth and fruit production, were not considered.

Figure 3.15 presents the total amount of water and nitrogen supplied by

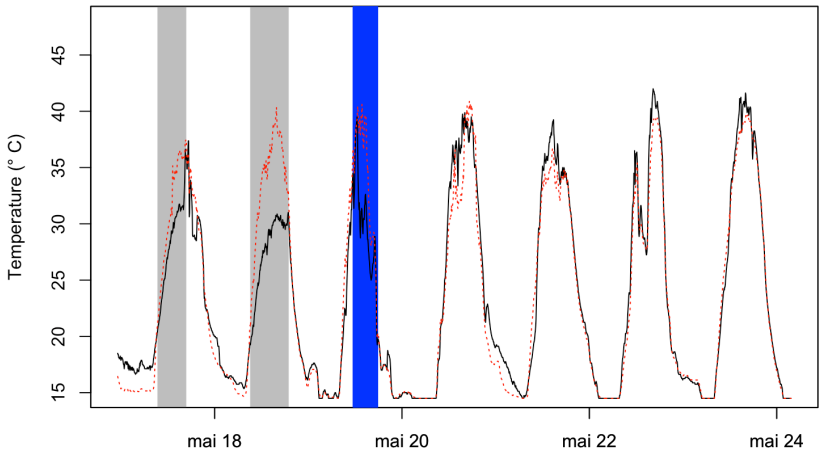


Figure 3.14: Example of temperature time series recorded with missing data for air temperature and showing "fake" plateaus (overlaid in blue). The black line is the irrigation pipe temperature. The missing records were replaced by the average temperature of the irrigation pipe on all the monitored plots in red doted line. The irrigation phases overlaid in grey were detected but required the confirmation of the farmer.

each farmer. These amounts vary from one farmer to another. Nitrogen supply ranged from 52 to 190 $kgN.ha^{-1}$. Variability was much higher for irrigation amounts, ranging from 260 to 2800mm.

Note that in some cases, the higher level of fertilization was, the higher amount of irrigation water (P1, P3 and P10). Inversely, other farmers associated high levels of fertilization to relatively low water supplies (P6, P9, P11, and P4, P5, P8 in some extent). There were also cases of both low N and water supply (P7), or more rarely, low N input and high amount of irrigation (P2).

The large variability in water supplies can partly be explained by the unit of the measurement used by the farmer. Indeed, irrigation is quantified in terms of duration and rarely in terms of amount of water supplied. To define the duration, farmers take into account their pump capacity, which they consider to define the water flow. For some of them, the lower there is horse power, the less is the flow delivered, and the longer should they irrigate. This led to long irrigation duration, even when water flow discharge was high.

Furthermore, the detailed fertigation schedule of each farmer is presented in figure 3.16. The farmer commonly defined key periods when irrigation was realized. Two main irrigation strategies were observed. On the one hand there was a strategy aiming at irrigating regularly, adjusting the frequency (about 3 to 7 days on average) and doses. This strategy was mainly powered by farmers of non-environmental-friendly clusters (Chapter 2) represented by P1, P6 (cluster 1), P3, P10 and P11 (cluster 2). On the other hand, there was a strategy comprising two irrigation phases, separated by a relatively long no-irrigation period, of

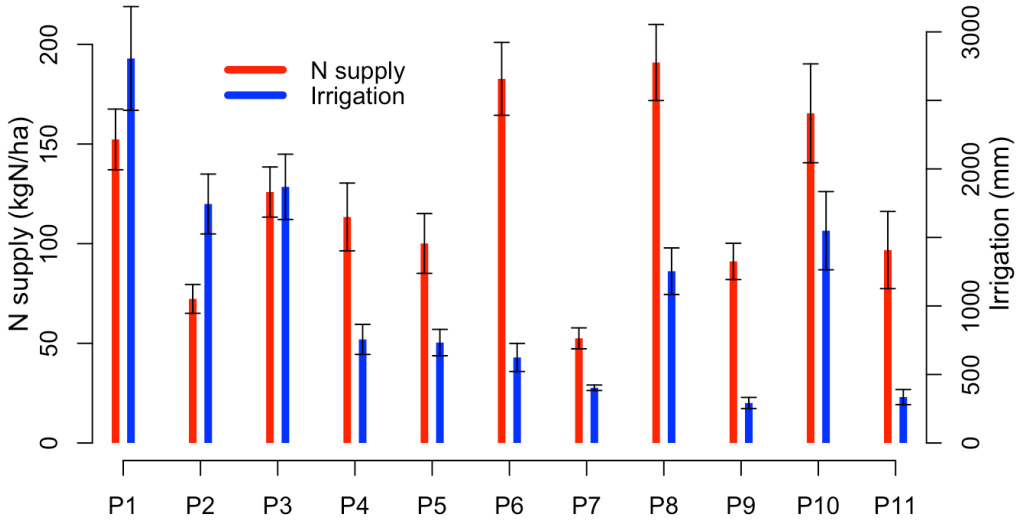


Figure 3.15: Total amount of irrigation water and nitrogen supply, for all monitored plots, for one cropping season.

up to thirty days or slightly more. This strategy was observed on intermediary cluster 3 (P4) and cluster 4 (P8) and environmental-friendly clusters 5 (P2) and 6 (P5, P7, P9). In the first irrigation phase, a small amount of water was brought to the plant, at transplantation and a couple of days after. In the second phase, as in the case of the first strategy, the frequency was adjusted by the farmer, depending on plant's demand. The doses generally increased with the plant development stages. On a daily time frame, farmers estimated the plant water demand based on climatic conditions and a possible state of plant stress. The decision to irrigate or not, also depended on arbitration and water sharing between different crops grown simultaneously.

Concerning nitrogen applications, doses were split into several applications. The doses basically depended on the type of fertilizer used. Two fertilization strategies were also observed. In a first strategy, an important amount of nitrogen was provided with DAP at transplantation (or a few days later), then several fertigation occurred between flowering and the first harvests (P1, P2, P4, P7, P8, P10, P11). When the farmer did not use DAP, another strategy consisted in spreading nitrogen supplies between flowering and the first harvests (P3, P6, P9). Before the first harvest (and sometimes during the harvest period), nitrogen was generally provided as Ammonium Nitrate. After the first harvests, farmers typically used calcium nitrate and magnesium nitrate to support fruit production.

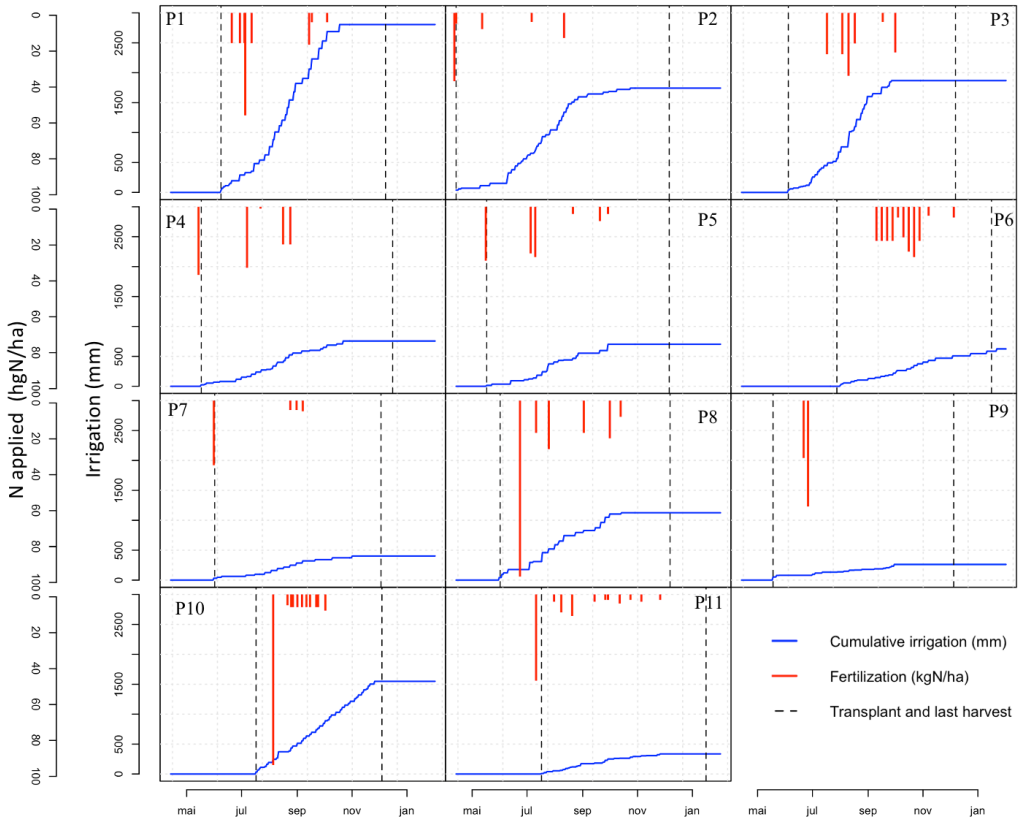


Figure 3.16: Cumulative amounts of irrigation water (blue lines), and nitrogen application (red bars), for all monitored fields, for one cropping season.

3.3.4 Above ground biomass and yield

This section focuses on yield and biomass in relation with variety, duration of the cropping cycle and the amounts of nitrogen and water supplied. The aboveground dry biomass at the last harvest is presented in figure 3.18(a). The total aboveground biomass ranged from 2 to 5 $T.ha^{-1}$ approximately. The higher values were observed on P1, P2 and P11 while P4, P7, P8 and P10.

We distinguish "marketable yield" and "dry yields" (also called "yields") as two variables of interest as the first is most interesting and informative for farmer, and the later is used to study agronomic processes. The contrasted management rules described in chapter 2, compounded with the diversity of fertigation practices presented above, resulted in a high yield variability across the plain. Indeed, the marketable yield ranged from 4.8 to more than 70 $T.ha^{-1}$ (Figure 3.18(b)). The median dry yield was about 2.5 $T.ha^{-1}$ (Figure 3.18 (c)) and it ranged from 1 to 7 $T.ha^{-1}$. This variability in yield was observed at three levels. First, yields varied according to variety. Indeed, the highest values were observed for the hybrid variety (P1, P2, P3). Inversely, the local variety generally presented lowest yields. Secondly, an important variability was observed within

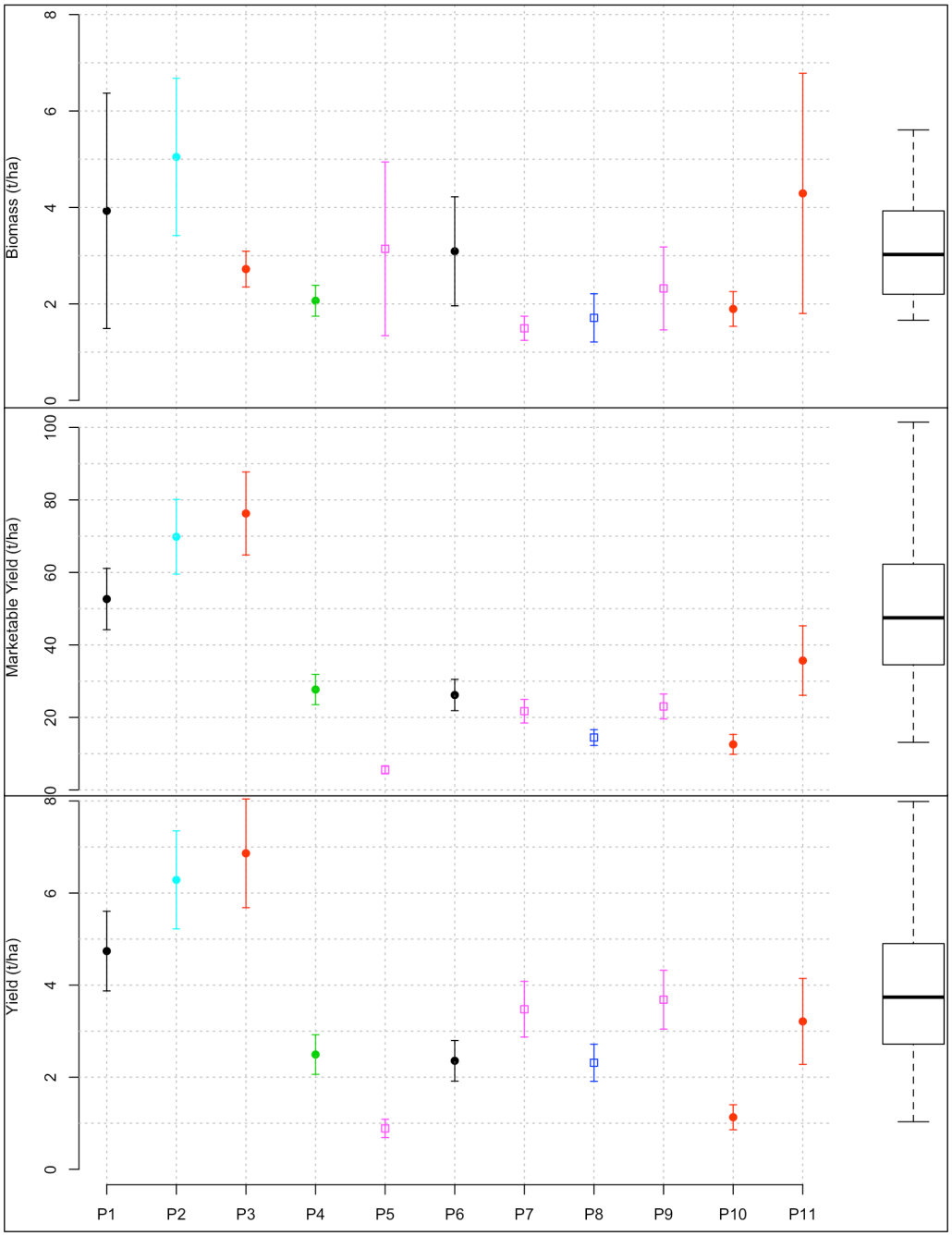


Figure 3.17: Observed dry biomass (a), marketable yield (b) and dry yiel (c) per plot (scatter plot) and dispersion (boxplot next to the scatter plot). The error bars represent the uncertainty related to each value. The dry yield was obtained by deducting the water content from the marketable yield: 91% for hybrid variety and 84% for local variety.

varieties. Interestingly, although yields were generally higher for the hybrid variety, the local variety produced similar dry yields on certain plots compared to the hybrid variety. Finally, variability was observed even for the fields of a same cluster (cluster 1, 2 and 6). That diversity might have probably been confirmed for the other clusters (3, 4 and 5), if there had been more than one plot monitored in the sample. The most important information that came out was that TMRs did not lead to similar yields independently of clusters.

3.3.5 Crop management data and yield diversity

Figure 3.18 presents the observed yields in relation with the duration of cropping cycle, supplied water and nitrogen amounts and planting density. The average duration of the cropping cycle was about 190 days, regardless of variety. As far as hybrid variety is concerned, a link was found between the duration of cycle and yields (and consequently, between yields and date of transplantation, since the last harvests occurred approximately in the same period). Indeed, as shown on figure 3.18 (a), yield increases with the duration of the cycle (P10, P6, P11, P1 and P3). A possible explanation is that, beyond management rules, the duration of cropping cycle allows more harvests and hence higher cumulative yields. Sufficient water and nitrogen can be at the origin of high yields on P1 and P3. But that is not valid for other fields. Regarding local variety, there was not a clear link between the yields and the variables considered here. Rather, yield variability appears to be the consequence of the combined effect of different technical operations.

3.4 Discussion

The major points that must be taken into account while interpreting the results presented in this chapter are: the diverse nature of the studied systems and the uncertainties associated with the collected data. One of the variables which highly impacted the results was the cultivated area as most of variables are linked to it. It was calculated considering the planting density and the total number of plants transplanted on each field. The number of plants is actually known approximately. Due to different sources of uncertainty, the amount of water applied per irrigation, the total irrigation amount, the amount of nitrogen fertilizer supplied, the yields and the aboveground biomass have a high level of uncertainty. The estimation of the plot area highly impacts these variables. Data related to local variety have a relatively high level of uncertainty because of missing informations and the assumptions that were made. However, although there is a high level of uncertainty, these are not at the origin of the observed diversity.

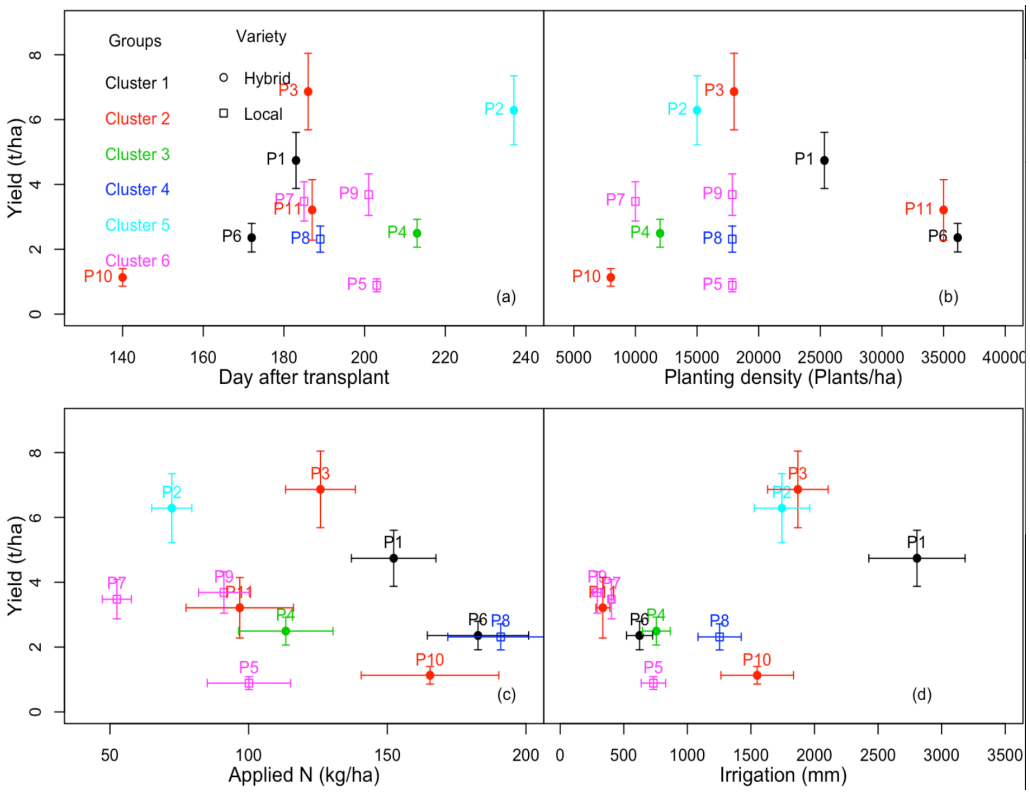


Figure 3.18: Observed yields and relevant management data: (a) number of days from planting to last harvest, (b) planting density, (c) N fertilizer applied, (d) total irrigation applied

Furthermore, inaccuracy in the fertigation calendars might come from the techniques of data collection and the spatial variability of applications in drip fertigated vegetable crops. Indeed, the applied amount of fertilizer were less precisely measured and might introduce inaccuracy in fertilization calendars. However, the TMRs monitored in 2019 were consistent compared to the data collected from the surveys of 2018 for the same plots. This shows that the approaches used to collect the data were robust and the information collected reliable.

The results showed an intra-cluster diversity of yield meaning that a non-environmental-friendly TMRs, which require high economic investment do not always lead to high productivity. Inversely, farmers were able to achieve higher productivities with more moderate management rules. Finally, yield variability might be explained by the combined effect of different management practices, and potentially other factors not taken into account so far. Operations such as pest and weeds management, the use K, P, Mg, Ca and organic fertilizer are not considered. To better explain the variability and the effect of farmers' management rules on yield, one needs an integrative conceptual framework allowing to represent farmers' practices and the biophysical processes occurring at plant

scale. Modelling lends well to realize such an exercise.

Chapter 4

Modelling and assessing environmental impacts of fertigation practices under field conditions: a case-study of chili-pepper using the Optirrig model.

Farmers' irrigation practices generally need significant changes and improvements to cope with agricultural water shortage, control nitrogen lixiviation and reduce yield gaps, especially in some Southern Mediterranean irrigated areas. The goals of this paper were first to reproduce and evaluate the fertigation strategies implemented by farmers to grow chili-pepper, in a highly-diversified irrigated area of Central Tunisia, then to propose alternative scenarios by modelling. The modelling approach consisted in running the Optirrig model for hydro-agronomical calculations (e.g. water drainage, nitrogen lixiviation, crop growth, water and nitrogen stress) fed by the management data for each plot, then by attempts at optimizing the fertigation strategies with objectives of increasing yields while reducing water and nitrogen losses. An appropriate design of fertigation (frequency, amounts) in coherence with soil properties was found relevant to both improve yields (by 1 to 4 tons/hectare, depending on the plots) and drastically reduce losses.

4.1 Introduction

Irrigated agriculture is responsible for about 70% of total freshwater withdrawals in the world (FAO, 2015). Drip irrigation which enables fertigation (fertilization through drip irrigation system), can benefit farmers through a decrease in water consumption and irrigation workload, and higher water and nitrogen productivity (Ravikumar et al., 2011). It also enables localized applications feeding plant roots and dose splitting according to plant requirements in time. However, drip irrigation may also contribute to soil and natural resources pollution (Benouniche et al., 2014) especially when improperly used to deliver excess irrigation (as pointed out by Venot et al., 2017). Vegetable production systems, for example, are among the main sources of diffuse agricultural pollution in the Southern Mediterranean irrigated areas, as a result of intensive fertigation strategies (Suárez-Rey et al., 2019). In these regions, the adoption of drip irrigation led to an increase of groundwater withdrawal (Massuel et al., 2017) and the paradox of increased pressure on groundwater from the use of an otherwise highly-efficient irrigation system was highlighted by Venot et al. (2017). Most farmers did not adapt their irrigation scheduling and amounts to this new technology, and even extended their irrigation surfaces, in a well-known rebound effect (Berbel and Mateos, 2014). By contrast, despite the need to address agricultural water shortage in general (Sharma and Irmak, 2020) and improve water and nitrogen productivity through the adoption of efficient fertigation strategies (Chauhdary et al., 2020), very few studies have sought to link the optimization issue and farmers' constraints and practices or habits (Benouniche et al., 2014; Laib et al., 2018) which is the scope this study.

When properly anchored in experimental studies through model fitting, running scenarios through modelling is an alternative and advanced technique to compare fertigation strategies and the associated agro-environmental variables (Chauhdary et al., 2020). It enables the estimation of water drainage and nitrogen lixiviation which are difficult to measure outside experimental stations, especially when studies involve multiple plots or large territories. A known requirement, especially within territories where farming practices are very diversified is that the model needs to accurately simulate the heterogeneous soil conditions and technical management routes. Uncertainty is the issue to handle before representativeness of the modelling can be claimed: when performing model-based analysis of a particular system, uncertainties in model parameters and in observed data combine and may affect the results to a large extent (Tohme et al., 2020). In deterministic approaches, the parameters are often case-specific, without any prior estimates when a system is described for the first time, and parameters are not always transposable when multiple sites are involved. In complement, Wallach et al. (2018) highlighted that obtaining the input data and

parameters necessary to run crop models is more difficult than evaluating their predictions.

The challenge is thus to use the right model, or at least one that is tuned to the available data and able to produce the variables of interest, and to identify the adequate calibration strategy, for unmeasured parameters required for model runs. There is a broad range of model calibration strategies to identify acceptable sets of parameter values out of in-situ experimentations. Among these strategies, there are manual "trial-and-error" attempts or automated approaches, e.g. gradient optimization, global or generalized Bayesian approach (Mailhol et al., 2011; Mailhol et al., 2018; Suárez-Rey et al., 2019; Tohme et al., 2020). It is altogether the context (data), the objective (variables) and the technical means at the modeller's disposal and the modeller's background in model exploration that dictate the choice of a calibration strategy (or the choice of complementary strategies for cross-validation to handle poorly-gauged contexts).

The goals of this paper are first, to describe the very diverse fertigation strategies (implemented in the same territory, leaning on the same water resources and affected by similar constraints) and second, to assess their agro-environmental impacts and drawbacks before testing alternative scenarios regarding irrigation scheduling, nitrogen applications to increase yields. This analysis focuses on chili-pepper crop fertigation strategies throughout one season, in the Merguellil downstream plain. As this crop is very representative of the vegetable crops grown in irrigated zones of Central Tunisia, an explicit and portable modelling procedure was built to be easily applied to other crops and contexts.

This paper is organized as follows. After presenting the sites and data, the methodology and the Optirrig model used are described. Then we present the procedures chosen for model fitting and to handle uncertainties in poorly-gauged contexts for the estimation of crop yield and water and nitrogen productivities followed by optimization attempts. Next, we present the outcomes of the calibration procedure, the analysis of modelling results and optimization results drawn from alternative scenarios. The last section is a discussion that focuses on providing realistic recommendations to bridge modelling results and experimental practices.

4.2 Materials and methods

4.2.1 Study sites and data acquisition

The study took place in the Merguellil downstream plain, an almost entirely irrigated plain in Central Tunisia. The Merguellil plain has been the subject of many studies describing the area, the local farming practices and the main stakes of

regional water management (e.g. Leduc et al., 2004; Goulven et al., 2009). Chili-pepper is one of the most widespread crops, incorporated in most cropping systems. Eleven chili-pepper cropping fields were monitored between April and December 2019 (Figure 4.1). The fields are not equipped for thorough monitoring of fertigation. Plots were chosen to represent the main types of technical management routes applied to chili-pepper in the zone, based on a previous study (Chapter 2). The farmer's agreement and interest in participating in the study were also taken into account for field selection. The experiment was carried out in an uncontrolled environment, in which all management rules were entirely designed by the farmers. In accordance, the affordable monitoring and measurements were designed to describe local farming practices at best. However, the challenging experimental conditions still resulted in multiple types and levels of uncertainty for each plot, and varying between plots. Overall, this is a poorly-gauged context even if data collection has been richer on some of the plots.

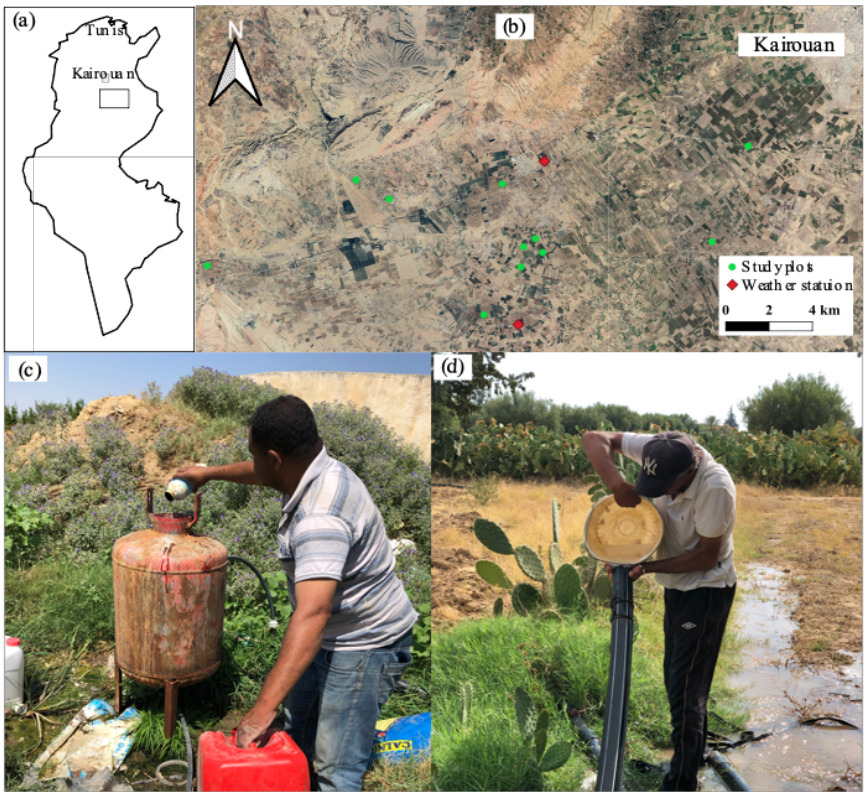


Figure 4.1: The Merguellil downstream plain (a) and location of the monitored plots and weather stations (b) with illustration of fertigation practices, as injection of fertilizers into the drip irrigation system (c) and injection of ammonium nitrate into the main irrigation pipe (d).

Management operations, in particular fertigation strategies, were monitored on each plot from the earliest transplant date to the latest harvest date (Table

4.1, Table 4.2). All plots were independent and no recommendations were made to the farmers. Two chili-pepper varieties were used: "hybrid" and "local". The dates of transplant ranged from April 12th to the end of July 27th and crop cycle durations were also variable, between 140 and 237 days. The P4, P7 and P10 plots comprised an extensive olive grove, for which the annual crop was planted within the inter-rows. Only the inter-row areas are considered in this study. Data on fertilization (nitrogen amounts and dates) were collected through weekly interviews with the farmers.

Table 4.1: Set of indicators describing irrigation strategies, in terms of doses and scheduling, implemented on each field. Irrigation dose indicators: AID, MAIA, MIIA are average, maximum and minimum irrigation dose, and TIA the total irrigation amount. Irrigation scheduling indicators: LDP is the longest dry period in the 120 first days after transplantation, ADI the average number of days between two irrigations and TNI the total number of irrigations

	Dose				Scheduling		
	AID (mm)	MAIA (mm)	MIIA (mm)	TIA (mm)	LDP (day)	ADI (day)	TNI (-)
P1	94	174	16	2806	8	4	30
P2	43	97	10	1744	20	5	41
P3	52	138	8	1869	9	4	36
P4	28	50	9	756	17	6	27
P5	37	105	8	702	20	8	19
P6	23	39	8	565	11	6	25
P7	27	36	15	373	26	9	14
P8	60	150	15	1081	23	8	18
P9	15	52	2	262	36	10	17
P10	37	104	16	1549	11	3	42
P11	13	33	3	335	14	5	26

As the fields were not equipped with a water meter, irrigation amounts and dates were determined indirectly, as follows. The irrigation duration was measured through an alternative, simple, low cost, robust and non-invasive method (Massuel et al., 2009), in which temperature loggers (Thermochron iButtons logger model DS1921H-F5) continuously monitored irrigation pipe temperature. Detection of irrigation timing, and hence its duration, resulted from the comparison of irrigation pipe and air temperatures. In parallel, the pumping rate was measured using an ultrasonic flow meter (Ultraflux Digisonic P). One single measurement was realized on each field, assuming the pumping rate was consistent over the cropping period. Irrigation duration and pumping rate allow to determine water consumption.

Agronomic, pedologic and climatic data were also collected. Leaf Area Index (LAI) and biomass production dynamics were measured on P6. LAI was estimated by scanning all leaves of a sample of plant and measuring total foliar

Table 4.2: : Soil properties and management data on each plot, FC is field capacity (measured at 3 bars), WP is wilting point (measured at 15 bars), CD is cycle duration and Σ N the cumulative nitrogen amounts

Plot	FC	WP	Variety	Transplant	Sunshine	CD (day)	$\Sigma N(\text{kgN.ha}^{-1})$
P1	0.20	0.096	Hybrid	07/06/2019	100%	183	113
P2	0.22	0.09	Hybrid	12/04/2019	100%	237	72
P3	0.24	0.09	Hybrid	03/06/2019	100%	186	102
P4	0.24	0.09	Hybrid	16/05/2019	70%	213	115
P5	0.20	0.09	Local	16/05/2019	100%	203	100
P6	0.12	0.04	Hybrid	27/07/2019	100%	172	182
P7	0.09	0.04	Local	31/05/2019	70%	185	52.5
P8	0.14	0.07	Local	31/05/2019	100%	189	191
P9	0.14	0.08	Local	17/05/2019	100%	201	91
P10	0.12	0.04	Hybrid	16/07/2019	70%	140	166
P11	0.12	0.04	Hybrid	25/07/2019	100%	143	99

surface, using the ImageJ software (Schneider et al., 2012). The aboveground dry biomass was measured for each plant after drying at 63 °C for 72 hours. Planting density ranged from 2.1 to 3.7 plants/m2. Further, four to ten harvests were realized, depending on the plots. Harvest dates were not predefined, they were decided from market conditions. It was impossible to know all harvest dates for all plots and thus three complementary methods were used as proxies to estimate marketable yield. First, the total weight of fruits harvested from the entire plot was measured, whenever possible. Second, three 25 m^2 quadrats were randomly installed within the plot, in which fresh yield was measured. Third, the farmer communicated the total number of harvested crates, and yield was then estimated, knowing the average weight of the crates. All three methods led to consistent estimations. Samples of fruits were oven-dried using the same principle as for dry biomass. On average, fruit water content was about 91% for the hybrid variety and 84% for the local variety. These numbers were used for conversion marketable yield into dry yield. Climatic data (rainfall, temperature, air relative humidity and solar radiation) were measured at a local weather station (Figure 4.1(b)). A 30% decrease of daily radiation was assumed for agroforestry systems on plots P4, P7 and P10. Reference evapotranspiration (ET0) was calculated using the Penman Monteith equation (Allen et al., 2011). A unique set of climatic data was finally used, as no significant differences were found between data from the two stations. Finally, soil texture on the eleven plots was heterogeneous with clay (P1, P2, P3, P4), clay or silt-sand (P5, P8, P9) and sandy types (P6, P10, P11) (Table 4.2). All soils were slightly alkaline, carbonated, with a low organic matter content.

4.2.2 Methodology

The global methodological approach was adapted from a framework proposed by Cheviron et al. (2016), which suggests three successive operations to optimize irrigation strategies: (i) sensitivity analysis to identify the key parameters, (ii) uncertainty analysis to identify the tolerable amount of uncertainty on the key parameters and (iii) attempts at optimizing irrigation dates and doses, relying on the previous information. Little is said, however, on the preliminary step of model parameterization, which consists here in testing and confronting two modelling approaches, seeking cross-validation (or at least complementary indications) to address the poorly-gauged context previously exposed.

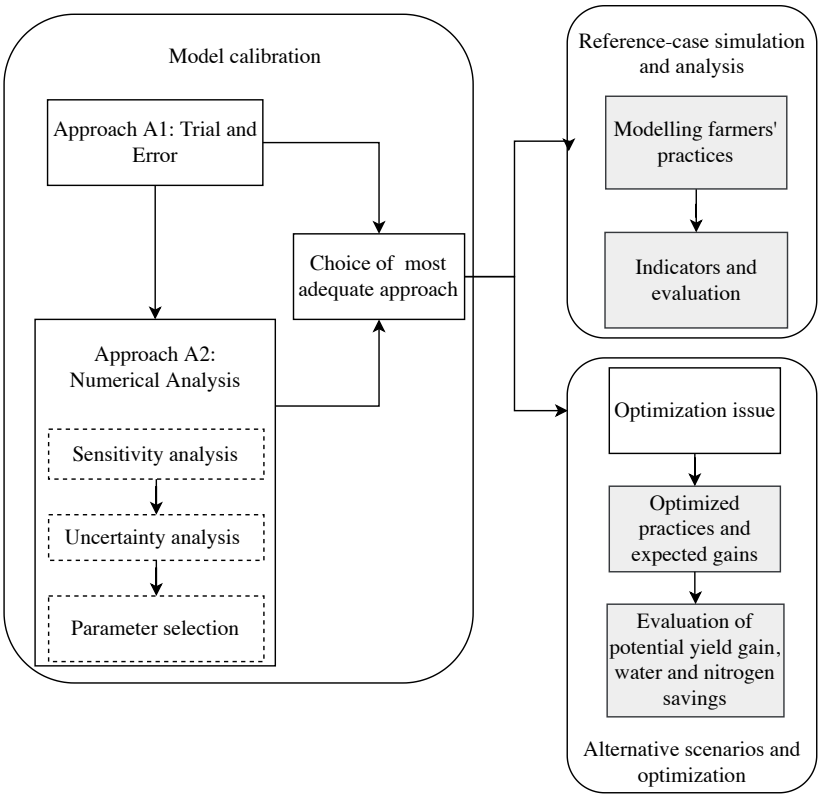


Figure 4.2: Framework of the study, with successive steps of semi-automated model calibration (sketch 1), reference-case simulation and analysis (sketch 2) and tentative optimization of farmers' practices through the formulation of alternative scenarios (sketch 3).

Approach A1 consisted in the calibration on one plot, in a deterministic procedure, resulting in a unique parameter set, later tested on all plots. Approach A2 resorts to a multi-stage calibration based on model analysis techniques, which aims at identifying a series of equifinal parameter sets. Approaches A1 and A2 are different by nature (deterministic vs. statistical) and by their objectives (single vs. multiple solutions) which allows fruitful comparisons. Once

model calibration is achieved and deemed acceptable (sketch 1, Figure 4.2), the analysis targets the key contextual variables and indicators (here, yield, water and nitrogen wastage, or the dynamics and severity of water and nitrogen stresses) (sketch 2, Figure 4.2). The final step is a tentative formulation of alternative scenarios for optimization purposes (here, yield gains, water and nitrogen savings, or reduced lixiviation) with indications for *in-situ* implementation (sketch 3, Figure 4.2).

4.2.3 The Optirrig model

This section gives an overview of model rationale and structure. Optirrig is an agro-hydrological model based on the PILOTE-N formalism and source code (Mailhol et al., 1997, 2011; Mailhol et al., 2018), rewritten in modern language and modular structure to easily include new processes and allow the generation, analysis and optimization of irrigation scenarios (Cheviron et al., 2016, 2020). It is used in particular to simulate yield as well as water and nitrogen budgets for fertigated and drip-irrigated vegetable crops (Elamri et al., 2018; Albasha et al., 2020). It is a three-reservoir hydrological model coupled to simplified crop growth and nitrogen balance models. Its advantage is to run with a limited number of required parameters, making it a practical tool for ungauged field applications (provided uncertainties are correctly handled). Figure 4.3 shows the backbone of the model, focusing on the link between model variables and omitting model parameters. Figure 4.3(a) describes calculations used for water and nitrogen management, where the nitrogen stress term SN is taken from Figure 4.3(b) and combined with the water stress term Sw with direct impacts on the LAI and TDM (aboveground total dry matter) variables, that propagate through the whole scheme.

In Optirrig, thermal time controls the S-shaped dynamics of LAI (with a correcting effect due to stresses) which in turn dictates actual evapotranspiration as the response to climatic demand. The cumulative nitrogen demand by the crop is another S-shaped function of TDM while nitrogen availability and uptake by the crop depend on nitrogen concentration in soil solution and on the LAI-dependent crop transpiration, respectively. This makes LAI the key model variable for most applications. The required inputs are (i) climatic data (daily air temperature, global radiation, reference evapotranspiration, rainfall), (ii) field management data (transplant and harvest dates, fertigation strategy as dates and doses of water and nitrogen applications) and (iii) parameters describing the soil and crop (wilting point, field capacity, soil depth, base temperature, maximum LAI, shape parameters of the LAI curve, maximum crop coefficient, shape parameters of the cumulated crop nitrogen demand, root growth rate). Almost all variables in figure 4.3 are simulated at a daily time-step, except the harvest

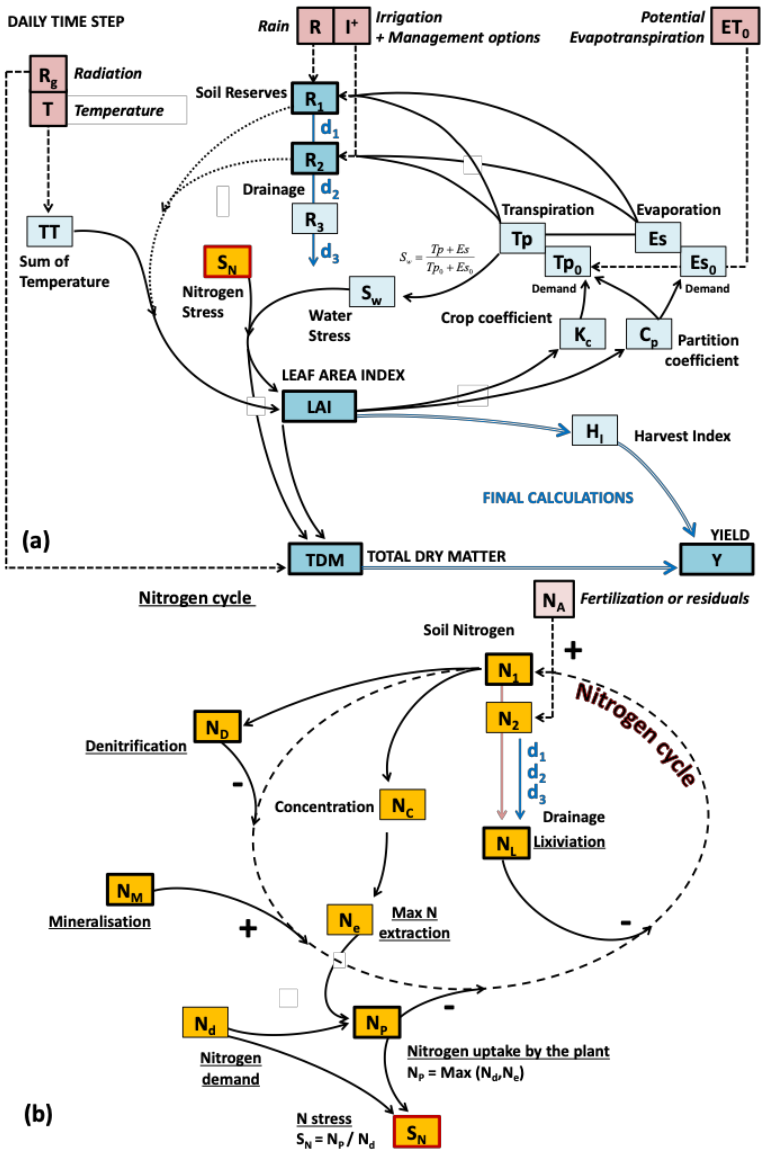


Figure 4.3: The structure and principle of the Optirrig model (from Cheviron et al., 2016, 2020) showing the link between model variables (a) and a focus on the simplified nitrogen cycle used (b). Both schemes connect through the nitrogen stress SN calculated in (b) and called in (a).

index and crop yield, that may be "anticipated" in the course of season (in the real-time mode of the model) but whose final values are only known at harvest.

4.2.4 Model calibration

Model parameters are not always transposable from a field condition to another. Although offering new facilities for numerical methods in comparison with the former PILOTE-N model, the Optirrig model has neither been used in multi-site

studies nor in poorly-gauged contexts, and only classical experiment-based calibrations were performed, for different crops(Mailhol et al., 1997; Elamri et al., 2018; Mailhol et al., 2018; Albasha et al., 2020). The enriched calibration procedure proposed here combines a "rather basic" deterministic approach (Approach A1 Figure 4.2, that targets the identification of the assumed best parameter set) and a multi-stage numerical approach (Approach A2 that targets the identification of acceptable parameter sets), expecting complementary indications and cross-validation from the comparison of their merits and drawbacks. Although illustrations are provided for chili-pepper grown in the Merguellil plain and the Optirrig model, general insights are also sought as the objective is to propose an easy-to-implement calibration method for handling new, poorly-gauged contexts. As shown in figure 4.2, the succession and confrontation of approaches A1 and A2 is expected to allow a suitable model calibration with insights on its merits and drawbacks, also seeking recipes for implementation in new contexts.

Approach A1 refers to a hand-made, deterministic calibration procedure, often consisting in trials-and-errors, whose outcome is the identification of the assumed best parameter set. Although not a formal guarantee that the calibration attempt will be successful and endowed with a clear physical sense, three "necessary but not sufficient" conditions should be met: (i) a common quantity is present on all plots (here, chili-pepper), (ii) informative-enough indications have been recorded for at least one of the mattering model variables, on one of the plots (here, the LAI and TDM dynamics on plot P6), and (iii) the modeler knows which parameters control the recorded variable (here, the shape parameters of the LAI curve with thermal time, which in turn dictate the shape of the TDM curve). The choice here is to adapt the deterministic calibration strategy used by Laib et al. (2018) in field conditions for greenhouse horticulture. Starting from an initial values of parameters obtained from a parent study (Albasha et al., 2020) and from expert knowledge, a trial-and-error process is used to adjust plant parameters and obtain the best match between model predictions and observations on plot P6. Then the same plant parameters are transposed to other plots, while using plot-specific information regarding soil depth and fertigation strategy. The underlying hypothesis is somehow that *"a fine-enough sampling of the key variable(s) on one of the plots is enough to catch most of the intrinsic model behavior by manual try-and-error attempts, then plot-specific adjustments are able to provide enough complementary indications"*.

Approach A2 advocates a multi-stage numerical calibration procedure that leans on model analysis techniques (sensitivity analysis, uncertainty analysis) to identify acceptable parameter sets, if any (as adapted from Rigosi et al., 2011;

Cheviron et al., 2016). Sensitivity analysis should encompass all relevant parameters (here, soil and plant parameters thought to have an influence on crop development and soil and nitrogen budget, not starting from scratch regarding knowledge on the model) and target the contextually-relevant model variables (here, the final values of crop yield, total dry matter, water drainage, nitrogen lixiviation, actual evapotranspiration and cumulative nitrogen uptake by the crop). Its outcome is the identification of the key model parameters, which are kept for the following stages while less sensitive parameters are left aside, i.e. keep the reference values issued from the A1 Approach. The following stage is uncertainty analysis on those key parameters: the perturbations applied on parameter values combine and propagate through the model, finally resulting in dispersion on model predictions. Within a possibly iterative process, this helps estimating which level of uncertainty is tolerable or if there should be any further effort in better determining some of the parameter values, so as to narrow the dispersion that affects model predictions. The third and final stage is to identify the acceptable parameter sets, i.e. those that yield results "close enough" to the observed data, again with the necessity to use information-rich observation data to usefully constrain the process, either visually (considering the envelope and shape of the curves) or numerically (considering user-defined objective functions).

Among multiple other possibilities, the choice here was to use the Morris method for sensitivity analysis (Morris, 1991; Campolongo et al., 2007) implemented through the R software (R Core Team, 2019) and one of its packages for sensitivity analysis ("Sensitivity" Iooss et al., 2020). This method performs a parsimonious screening of the parameter space, in predefined realistic parameter ranges, and stores the "elementary effects", i.e., the effects on model predictions obtained from small changes in one or several parameters at-a-time. Each parameter is then attributed two sensitivity scores, μ^* that measures its mean effect when varied individually and σ that measures its effect when varied with at least one other parameter, i.e. the strength of correlation effects, for the tested parameter. The Morris method is said multilocal rather than global, as its results are obtained from a limited series of well-identified and user-controlled trajectories in parameter space, and not from "blind" statistical evaluations that would hold for the entire parameter space with no further indication. A rather large set of 28 model parameters was tested (Table 4.3) in ranges of $\pm$20% around their reference values, and the final values of the contextually-relevant model output variables were chosen as targets of the analysis (crop yield, aboveground biomass, cumulative actual evapotranspiration, cumulative drainage, cumulative nitrate leaching, cumulative nitrogen uptake by the crop).

Table 4.3: Reference values for the tested model parameters.* Value specific to local variety

Parameter	Description	Unit	Value
pmax	Maximal soil or rooting depth	m	0.4
ksol	Soil resistance to evapotranspiration	-	0.27
tbase	Base temperature	°C	10
ts1	First critical growth stage	°C	600 (800*)
ts2	Second critical growth stage	°C	3720
tmaxlai	Thermal time to reach the maximum LAI	°C	1670
vroot	Root growth rate	m/d	0.0054
kcmax	Maximal Kc (crop coefficient) value	-	1.15
rue	Radiation Use Efficiency	g/MJ/d	0.35
hipot	Potential Harvest Index (if no stress)	-	0.7
estresslai	Harmfulness of water stresses on LAI	-	1
estresstdm	Harmfulness of water stresses on TDM (biomass production)	-	1
alpha1	1 Shape coefficient for the LAI curve	-	4.4
alpha2	2 Shape coefficient for the LAI curve	-	1.7
beta	3 Shape coefficient for the LAI curve	-	2.8
laiopt	Optimal mean LAI value between ts1 and ts2	m^2/m^2	0.7
penhi	Penalization coefficient for mean LAI values under laiopt	-	0.1
dens	Planting density	$Plant.m^2$	3.7
LAI0	Initial LAI value at planting	m^2/m^2	0.002
vmpot	Potential mineralization rate	$kgN.ha^{-1}.d^{-1}$	0.01
pcnresi	Mass percentage of carbon in soil residuals	%	2
minerap	Mineralization ratio	-	0.5
tdmmax	Maximal biomass	$T.ha^{-1}$	20
dnmax	Maximal plant N demand	$kg.ha^{-1}$	200
x1	Shape coefficient for the cumulative nitrogen demand	-	3
x2	Shape coefficient for the cumulative nitrogen demand	-	2
effabs	Efficiency of nitrogen absorption by plant roots	-	5
estressN	Harmfulness of nitrogen stress on LAI and TDM	-	1

Next, after the sensitivity analysis stage, the uncertainty analysis was performed with the GLUE method (Generalized Likelihood Uncertainty Estimation: Ferre et al., 2007; Yan et al., 2020), keeping only the sensitive parameters and ranging them in the same parameter ranges. The method consisted here in the generation of 10^5 combinations of parameter values through random perturbations of the reference values (using a latin hypercube sampling method), then in running the model for all combinations and finally in selecting equally plausible, said equifinal parameter sets. The selected sets are these with a likelihood score above a certain threshold, where the likelihood score is an appropriate

user-defined objective function, in which the weight of simulations close to observations is all the more heavy as the error on observations is tiny. Here, the selected sets were those within the 90% probability band around the observed data. The observation data used yields (in opposition to LAI and TDM dynamics on Approach A1). Additional calibrations have also been tried on plots P1 and P9, relying on final crop yield measurements only, for the sake of comparisons. This was to investigate the effect of plot subdivision into early season local variety plots (P5, P7, P8, P9), early season hybrid plots (P1, P2, P3, P4) and off-season hybrid plots (P6, P10, P11), i.e. more precise dynamics for the key model variable (LAI as a proxy for crop growth) but less information to rely upon for calibration. Overall, the underlying hypothesis in Approach A2 is that "the amount of uncertainty in the system prevents making any better than identifying equally plausible parameter sets, and these should be obtained from a fine-enough sampling of the key model variable(s) on one of the plots, before testing them on the other plots".

4.2.5 Reference-case simulation and performance indicators

The aim of this section is to indicate how farmers' practices are modelled and which indicators are used for comparison and evaluation. Optirrig produces multiple daily and seasonal variables, among which the LAI and TDM dynamics to be compared with observations, whenever available, and the final values of the already-mentioned contextually-relevant variables (crop yield, aboveground biomass, cumulative actual evapotranspiration, cumulative drainage, cumulative nitrate leaching, cumulative nitrogen uptake by the crop). In addition, emphasis is placed on the dynamics and magnitude of water and nitrogen stresses, clearly associated with the fertigation strategies put into practice and known to control crop growth, biomass production and yield.

For comparison and evaluation purposes, several indicators of productivity, efficiency and gains from optimization of irrigation and fertigation strategies are proposed (Table 4.4). Within the wide range of indicators available to assess irrigation performance, we consider water productivity and application indicators more generic and suitable to the study context. When combined to those provided in Table 4.1, these form the set of indicators available to characterize (Table 4.1) and evaluate (Table 4.4) the fertigation strategies.

4.2.6 Alternative scenarios and optimization

This section presents the optimization step performed from a numerical point of view by exploring alternative scenarios. This step aimed at converting the analysis into recommendations for *in-situ* implementation.

Table 4.4: : Indicators of productivity, efficiency and gains from optimization. "Opt" stands for "Optimized"

Indicator	Definitions
$WP = \frac{Y}{I+P}$ (4.1)	where WP (kg mm-1) is the water productivity; P (mm) is the total rainfall during the cropping cycle ; I (mm) is the total irrigation and Y ($kg.ha^{-1}$)the observed dry yield.
$WAE = 100 * (1 - \frac{D}{I+P})$ (4.2)	WAE (-): water application efficiency D: total drainage (mm)
$NUE = \frac{Y}{Nsupply + Ninitial})$ (4.3)	NUE: nitrogen use efficiency ($kg.kgN^{-1}$); Nsupply: nitrogen supply by fertilization ($kgN.ha^{-1}$); $N_initial$: $initialsoilnitrogenreserve$(kgN.ha^{-1})
$WS = \frac{Iopt - I}{I}$ (4.4)	WS: potential water saving (-); Iopt: optimized irrigation amount (mm)
$NS = \frac{Nlix - Nlixopt}{Nsupply + Ninitial}$ (4.5)	NS (-): potential of nitrogen saving; Nlix ($kgN.ha^{-1}$): nitrate leaching in farmers' fertigation strategies ;Nlix$_opt$(kgN.ha^{-1}): nitrate leaching in optimized fertigation strategies
$YG = \frac{Y}{Yopt} * 100$ (4.6)	YG (%): potential yield gain; Yopt ($kg.ha^{-1}$): maximal potential yield with optimized strategies

The underlying objective is to identify optimal fertigation strategies for each plot, in which neither water nor nitrogen stresses occur, while no water drainage or nitrate leaching are caused, thus a fragile compromise between sufficient and excessive applications. The challenge is thus to efficiently manage soil water reserve (which also controls nitrogen fluxes as nitrate transfers occur in solution) and to formally describe the problem in terms of model variables and operating constraints. The simplest way to address the issue and provide a reference scenario is to seek irrigation scenarios (and thus the associated irrigation triggers) able to fulfill daily evaporation and transpiration demands, then to eventually adjust nitrogen inputs in a second phase. The control variable is the ratio (Ratio, -) of total available soil water (TASW, mm) on useful reserve (RU, mm) evaluated daily (d) on the rooting depth:

$$Ratio(d) = \frac{TASW(d)}{RU(d)} \tag{4.7}$$

It is a feature of Optirrig to trigger irrigation only when the following combined conditions are met:

$$\begin{cases} Ratio(d) < Th \\ ASW_{R1}(d) < ETM(d) \end{cases} \tag{4.8}$$

where Th (-) is a user-defined threshold, ASW_{R1} (mm) is the available soil water in the (surface) R1 reservoir (Figure 4.3). In such a case, a possible fine-tuning of the model is to set the irrigation amount (I, mm) so as to fully complement the deficit of soil water reserve:

$$I(d) = RU(d) - TASW(d) \tag{4.9}$$

4.3 Results

4.3.1 Model calibration: approach A1 (trial-and-error)

Approach A1 consists first in deciding which parameters to adjust, which relies on the modeler's perception of the context (Which are the dominant physical processes and the targets of the analysis? What are the reliable parameters that do not need adjustments?) as well as on prior knowledge of the model itself (Which have been the controlling, sensitive parameters in similar contexts? What is known from model derivation and encryption in algorithms?). The trial-and-error attempts targets the shape parameters of the LAI curve, the temperature parameters, as well as the parameters attached to plant water and nitrogen demands, biomass and yield production (see Table 4.3). Optirrig offers the possibility to easily play with model parameters; the manual trial-and-error adjustment lead to a satisfactory representation of observed LAI and dry biomass dynamics on plot P6 (Figure 4.4), but also on the final crop yield. The simulated decrease of the LAI curve in its final stages is related to the stresses that regulate the plant growth.

4.3.2 Approach A2: Numerical Analysis

The first step in the A2 Approach was sensitivity analysis. The Morris method was applied to explore the sensitivity of Optirrig to variations of the whole set of 28 parameters listed in Table 4.3, reporting the effects on the selected six contextually-relevant model output variables (crop yield, aboveground biomass, cumulative actual evapotranspiration, cumulative drainage, cumulative nitrate leaching, cumulative nitrogen uptake by the crop). The analysis showed that

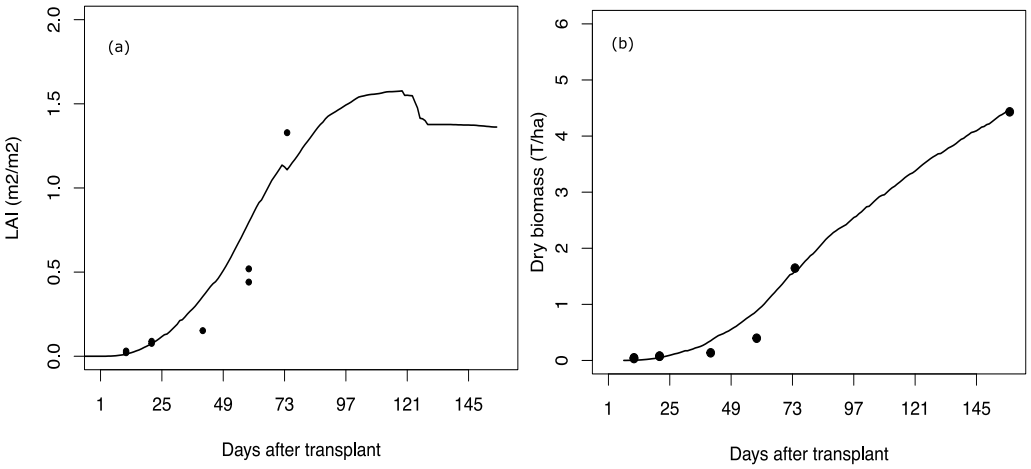


Figure 4.4: LAI - Leaf Area Index curve (a) and TDM – Total aboveground Dry Biomass curve (b) obtained on plot P6 from the Trial-and-error calibration of Approach A1

six parameters had a significant influence on the variables of interest: these are the parameters whose names appear outside the shaded regions in the (a) to (f) plots of Figure 4.5.

The maximum aboveground biomass and yield are strongly correlated, as it can be seen in Figure 4.3, yield is computed as the product of biomass times the harvest index). In accordance, both the aboveground biomass and yield are influenced by variations of the base temperature of the crop (tbase), the temperature sum necessary to reach the maximum LAI value (tmaxlai) and radiation use efficiency (rue). As expected, given the cited link between yield and biomass, only yield was influenced by variations of the potential harvest index (hipot). Water-related variables (drainage and total actual evapotranspiration AET) are also influenced by variations of tbase, tmaxlai and the maximum value of the crop coefficient (kcmax: controls the magnitude of the fluxes in response to the climatic demand). The fact that the variations of kcmax were not very influential for the final values of yield and biomass tends to indicate that water was brought in excess or at least that irrigation practices have not been thought to follow the dynamics of plant demands (to be confirmed). Otherwise, the tested increases of kcmax would have impacted the expected biomass production and yield in cases where not enough water would have been present in the system to match plant demands. Together with tmaxlai and rue, the maximal potential biomass (tdmmax) and one of the shape parameters of the curve that depicts the cumulative nitrogen plan demand (x2) have a significant influence on nitrogen-related variables (nitrate leaching and plant nitrogen uptake). These six sensitive parameters required fine-tuning calibration, which was undertaken in the GLUE selection process.

The second step in the A2 Approach is uncertainty analysis, applied to the

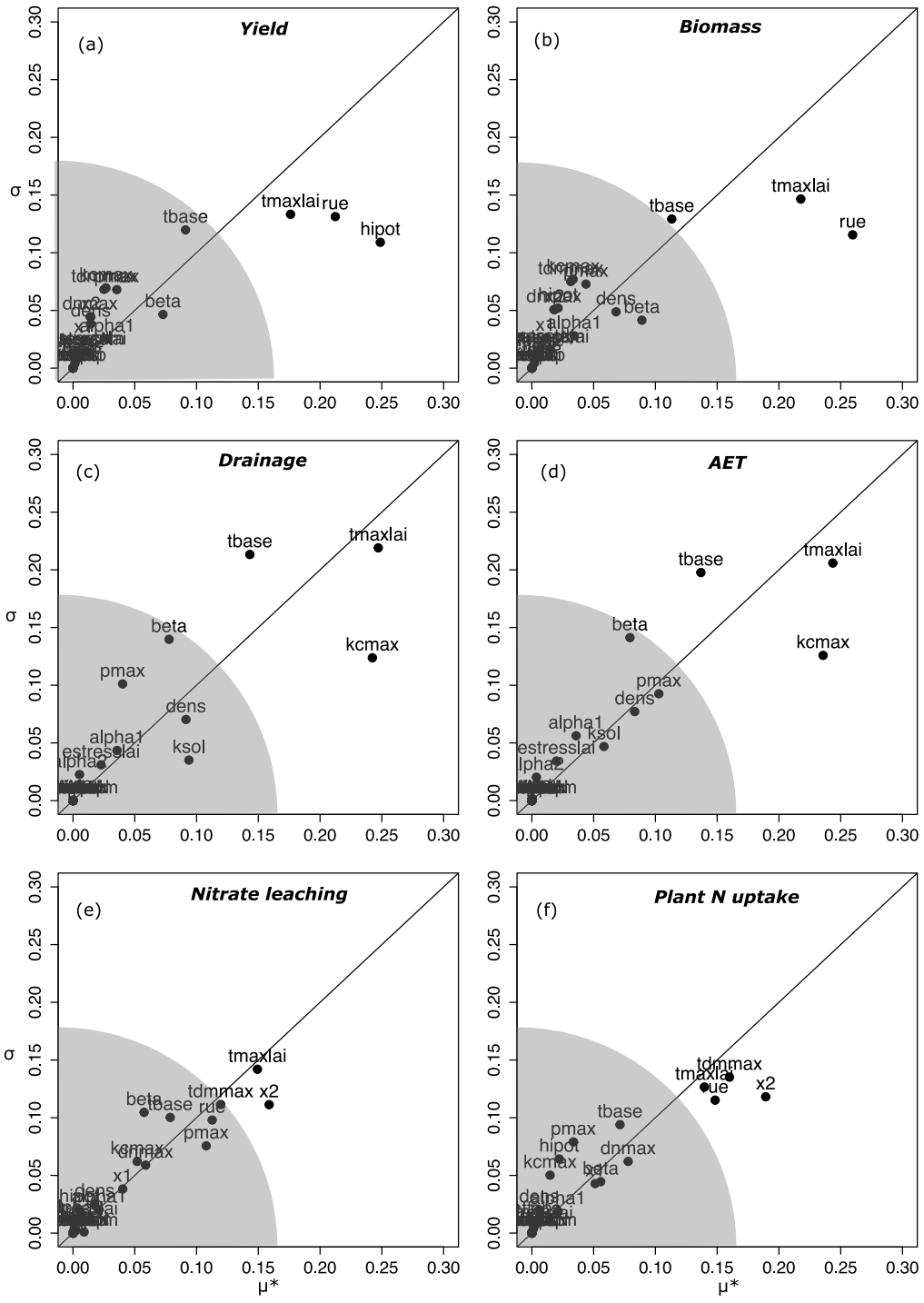


Figure 4.5: Results of the sensitivity analysis performed with the Morris method on the Optirrig model, targeting six variables of interest: final crop yield (a), final aboveground biomass (b), cumulative drainage (c), cumulative actual evapotranspiration (d), cumulative nitrate leaching (e) and cumulative plant nitrogen uptake (f).

previously identified sensitive parameters. This uncertainty analysis aims at the selection of a limited number of equifinal parameter sets, performing the same

work for the 3 sub-group of plots cited in Section 2.4: early season local variety plots (P5, P7, P8, P9), early season hybrid plots (P1, P2, P3, P4) and off-season hybrid plots (P6, P10, P11), "represented" by the P9, P1 and P6 plots, respectively. Among the initial 10^5 parameter sets generated to perform the GLUE analysis, only 8 parameter sets for P9, 211 for P1 and 1496 for P6 passed the selection criteria, i.e. "yielded results within the 90% probability band around the observed data".

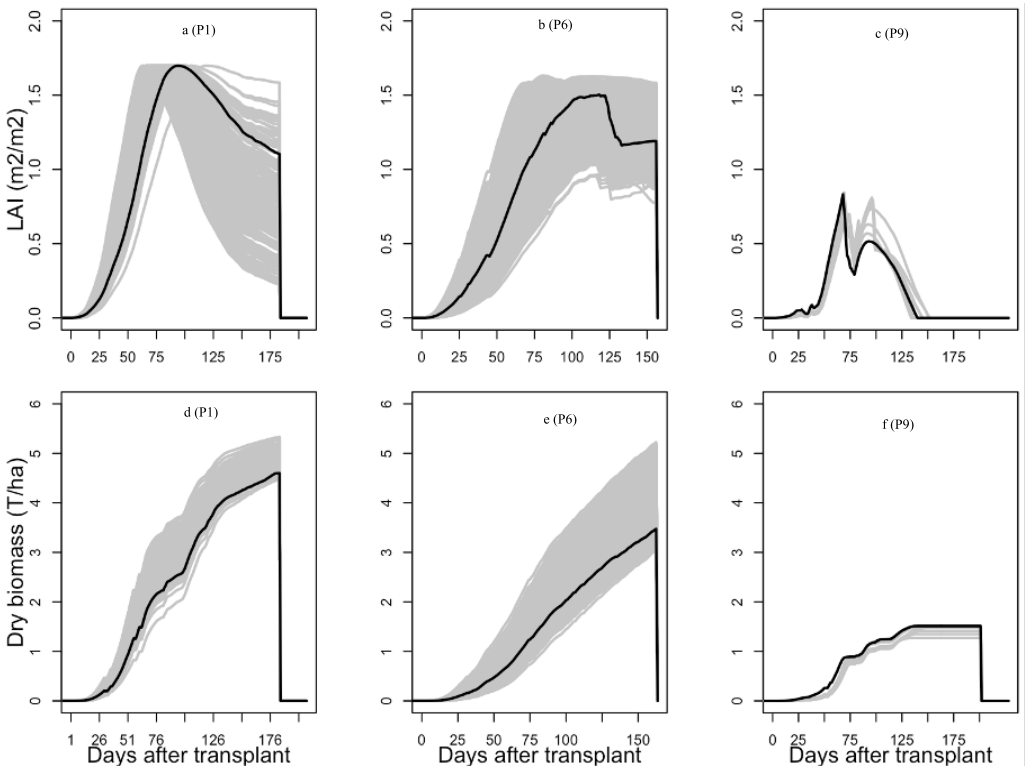


Figure 4.6: LAI (a, b, c) and TDM (d, e, f) curves for the accepted ("behavioral") parameters sets (in grey) on plots P1 (a, d), P6 (b, e) and P9 (c, f). The black line represents an example of one parameter set

This uncertainty band refers both to the available observation and absolute and user-defined acceptable dispersion of the predictions. Hence, a possible explanation for the fact that far more predictions are "accepted" on the plot that has rich observation data (LAI and TDM dynamics plus the final yield value on P6) than on the other plots (only final yield values on P1 and P9): more "accepted" predictions may be related to better constrained hence less dispersed predictions (the case of P6). On the other hand, 8, 211 and even 1496 are very small in comparison to 10^5 and the procedure may still be considered as selective. Further, figure 4.6 shows the LAI and TDM curves obtained on plots P1, P6 and P9 by running the model with the accepted parameters sets. In coherence with the above statements, the dispersion shown is not strictly correlated with

the number of simulations accepted. The parameter sets selected gave acceptable simulation in most cases. The LAI curve of P9 represents a particular case of high and long stress condition not well represented by the model. Further, the uncertainty range considered for the six sensitive parameters generated a broad range of curves for P1 and P6.

4.3.3 Merits and drawbacks of both approaches

This section compares the ability of both approaches to produce acceptable simulations of yields on all plots. The deterministic approach A1 was less suitable to simulate yield in the context of poorly-gauged and highly diversified farming practices (Figure 4.7). Indeed, the adjusted r^2 of the linear regression of observed

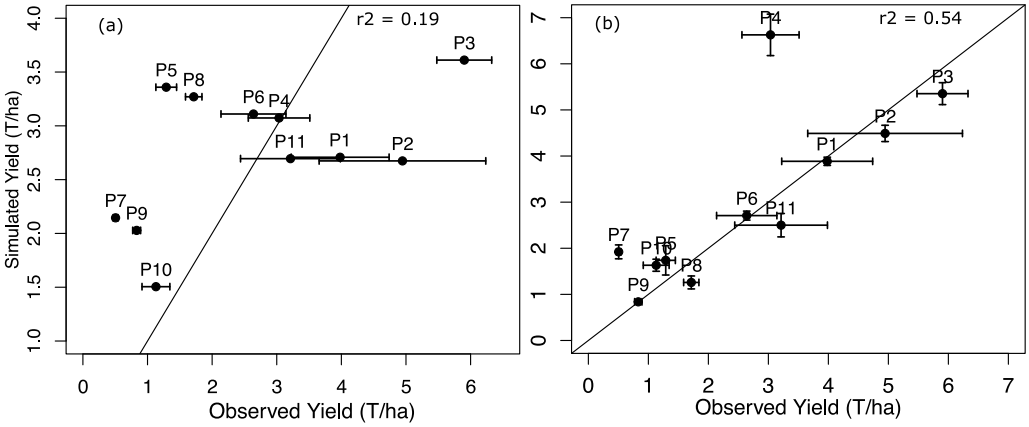


Figure 4.7: Observed and simulated yields: (a) approach 1 and (b) approach 2. The black oblique line represents the 1:1 axis. Vertical bars represent simulations error while horizontal bars represent measurement error.

to simulated yields was 0.19 with approach 1. Yield on local variety plots was systematically overestimated? It only ranged between 1.5 and 3.5 T/ha for the other plots. Inversely, r^2 was equal to 0.54 in approach 2. The two subgroups of hybrid varieties were globally well simulated, as all the estimation error bars almost cut the 1:1 axis. However, yield on P4 was largely overestimated. Concerning the local variety subgroup, yields were either underestimated or overestimated. Nevertheless, the simulations appear acceptable. Considering the model was proven robust to represent integrated biophysical processes of water transfer, N balance and crop growth for a wide range of crops and conditions, it can be assumed that the representation of water and nitrogen budgets on the study plots using approach 2 are also acceptable. Drainage and nitrate leaching on each plot are compared in the next section.

4.3.4 Reference case simulation and analysis

4.3.4.1 Modelling farmers' practices: water and nitrogen budgets

This section summarizes the effects of farmers' fertigation strategies, using the A2 modelling approach. Strategies implemented by farmers often result in resource overuse and wastage. Indeed, water and nitrogen budgets (Figure 4.8) revealed massive water drainage and nitrate leaching on almost all fields. Although some farmers irrigated massively and others more moderately, important amounts of water relative to applied amounts are drained out of the crop root zone. Note that similar wastage were simulated for nitrogen. Drainage ranged from around 200 mm to almost 2500 mm, representing 39% to 84% of irrigation, while nitrate leaching ranged from 100 to around 210 $kgN.ha^{-1}$. Fur-

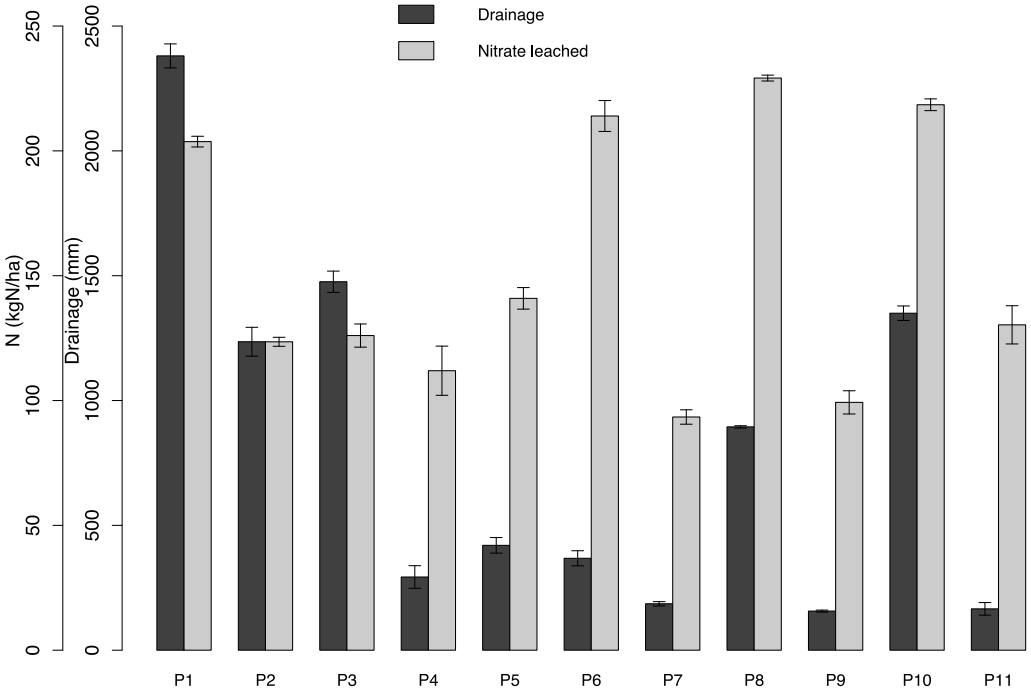


Figure 4.8: simulated water drainage and nitrate leaching for each field.

ther, important drainage was systematically associated with important nitrate leaching. But the opposite was not always valid. Indeed, even though drainage on P3, P4, P6, P11 and even P9 were slightly inferior compared to other fields, nitrate leaching was not much less. Rather, nitrate leaching simulated on P6 for instance was among the highest while drainage was among the lowest. These results suggest that irrigation strategies basically drive nitrate leaching, resulting in high amounts of nitrate leaching, even the more when high quantities of nitrogen are supplied (P1, P6, P8, P10 for instance).

4.3.4.2 Modelling farmers' practices: water and nitrogen stresses

In this section, the fertigation strategies are compared in terms of water and nitrogen stresses occurrence. Simulations revealed that water supply was not efficiently distributed over the time on all fields. Indeed, on all fields, crops were under water and/or nitrogen stress over a part of the cropping cycle (Figure 4.9). Local variety fields (P5, P7, P8, and P9) were among the most stressed. On these

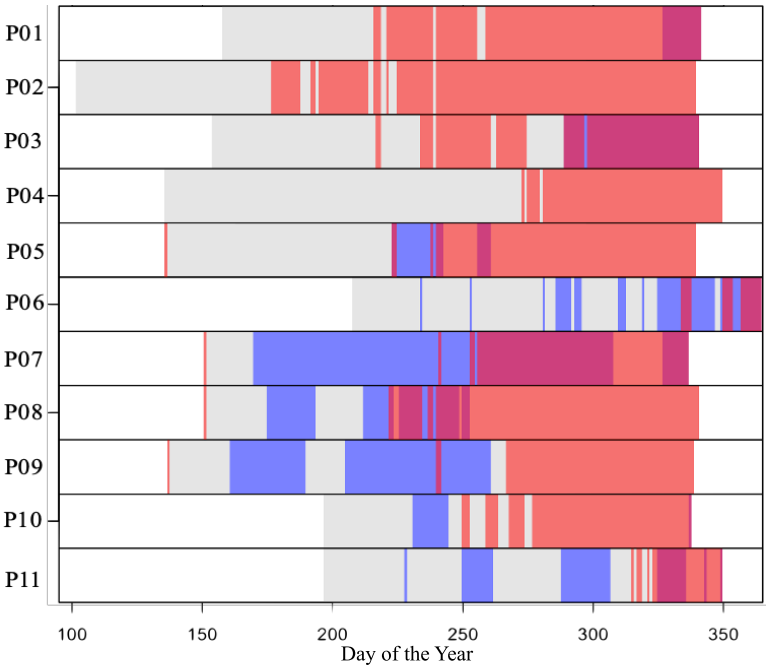


Figure 4.9: Water and nitrogen stress occurrences throughout the cropping cycle: red bands represent nitrogen stress, blue bands represent water stress, with their resulting intersection on purple, grey bands represent crop growth period.

fields, water stress primarily occurred during the first week of cultivation. This can be explained by LDP indicator (longest dry period in the 120 first days after transplantation, Table 4.1) which describes the number of days the farmers willingly do not irrigate in their fertigation strategy. LDP ranged from 20 to 36 days for these fields generating relatively long periods of water stress. Water stress is followed by consistent nitrogen stress on these fields, sometimes both were concomitant as for P7. This might be related to the massive drainage and consequently nitrate leaching generated by the fertigation strategies as described previously. Further, although LDP was equal to 20 for P2, no water stress was simulated. This can be explained by the fact that soil water reserve (facilitated by clayey soil on that field) was sufficient to cover crop requirement. P1, P2, P3, and P4 presented the highest RU (FC-WP) of the sample. Interestingly, no water stress was simulated for P2 and P4; and it only occurred during the last days of cultivation on P1 and P3. However, as for P5, P7, P8, and P9, nitrogen stress

occurred, consequence of the massive drainage. Finally, some periods of both water and nitrogen stress were simulated for P6, P10, P11, often shorter (P6 an P11) than in the other cases. This could be explained by most frequent irrigation and sufficient nitrogen supplies.

4.3.5 Alternative scenarios and optimization

4.3.5.1 Optimized practices and expected gains

This section summarizes the possible contributions of this study for improved plot-level fertigation strategies. The optimization was focused on irrigation scheduling (doses and dates). Figure 4.10 shows the potential yield gains and water and nitrogen savings achievable through an upgrade of current farmer's fertigation strategies. It shows that P6 and P11 were approximately at the optimum of the yield. However an economy was possible in terms of nitrogen use for both fields; and water use for P6. For the other cases, yields might be increased by 1 to 4 $T.ha^{-1}$ on average depending on the plot. In most cases, substantial reductions in water supply can be achieved. For instance, 1000 to 2300 mm of water could be saved on P1, P2, P3 and P10 and relatively less on P4, P5, and P8. However, P7 and P9 currently irrigate less than necessary and irrigation amount should be increased by 200 to 300 mm respectively in order to achieve higher yields. Furthermore, the optimized scenario generated, by limiting drainage, enables more nitrogen available for plants limiting nitrogen.

Moreover, figure 4.11 (complementary to figure 4.10) compares both farmers' strategies and optimized ones in terms productivity and efficiency. We note that P11 and P6 (to some extent) stand out from the other plots in terms of water productivity. As shown in figure 4.11, the highest values of water productivity (WP) were obtained for these two plots. As yields were almost at maximum potential values, NUE should not be significantly improved with the optimized irrigation strategy. However, 55 and 62% of nitrogen applications could be saved respectively for both plots, enabling a higher NUE. Water productivity could only be improved in the case of these two fields through a reduced water consumption. As far as the other fields are concerned, although nitrogen saving are possible, upgrading only irrigation scheduling should improve both water productivity and nitrogen use efficiency. Further, with current farmers' strategies, only 17 to 66% (WAE) of irrigation water (or less considering rainfall) is uptaken by plants. WAE should be substantially increased (by 93 to 100%) with the optimization scenario (WAE opt) which should higher yields by 12 to 86%.

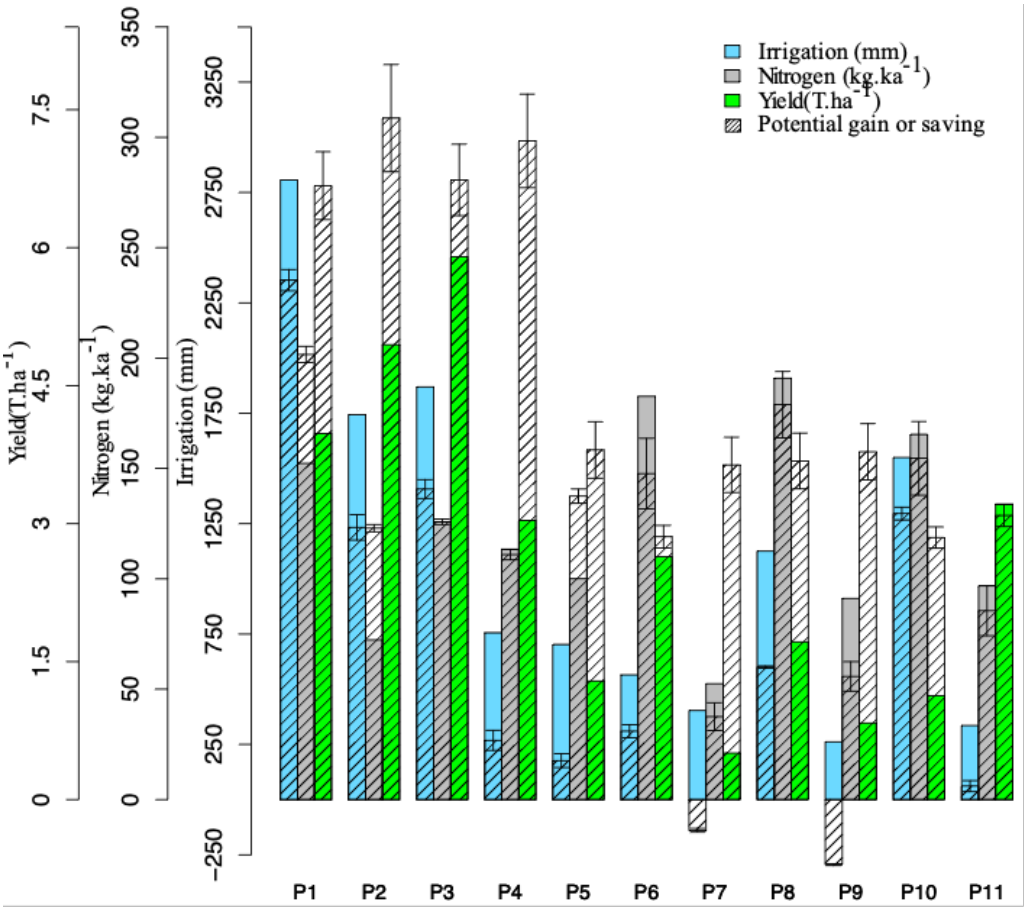


Figure 4.10: Potential yield gains and economy in the use of both water and nitrogen resources by plot, resulting from model optimization of fertigation strategies.

	WP	WP_opt	WAE	WAE_opt	NUE	NUE_opt	WS	NS	YG
	kg/ha/mm	kg/ha/mm	%	%	kg/kgN	kg/kgN	%	%	%
P1	1.4	12.9	17.6	99.7	18.9	31.7	84.5	95.9	40
P2	2.7	12.2	33.5	99.9	38	56.9	71.8	94.3	33
P3	3	12.9	24.4	100	31.9	36.4	76.5	68	12
P4	3.5	12.5	66.1	99.8	19	44.9	38.6	69.5	58
P5	1.6	6	48.1	99.6	8.3	24.5	25.3	88.6	66
P6	4.1	8.6	42.7	93.3	11.1	12	54.8	62.1	8
P7	1.1	5.9	59	92.7	4.7	33.8	0	35	86
P8	1.5	6.1	23.2	97.1	7	15	51.5	72.7	53
P9	2.3	5.7	57.5	95.5	5.8	26.2	0	47.7	78
P10	0.7	8.8	16.8	93.6	5.1	12.8	83.8	70.4	60
P11	7.8	8.9	60	93.7	20.8	20	20.1	55.3	0

Figure 4.11: Indicators of productivity and resource use efficiency. Indicators with "opt" represent value computed for the optimized strategy. WP: Water Productivity; WAE: Water application efficiency; NUE: Nitrogen Use Efficiency; WS: Water saving; NS: Nitrogen saving; YG: Yield gain.

4.3.5.2 Description of the optimized scenario

We notice that in general, better performances could be achieved in most cases by reducing doses per irrigation and hence total irrigation amounts and increasing the average irrigation frequency. Example of an optimized strategy generated by one parameter set is described Table 4.5 using a set of indicators. The threshold of Ratio (filling percentage of the root zone reserve) that triggers irrigation ranged from 55 to 75%. The optimized strategy deletes all water stress leading to almost no nitrogen stress (except 1 day for P5 and P8 and 3 days for P7). The dry period (LDP) to observe during the growing period is much higher on P1, P2, P3, P4, and P5 than in current farmers' strategies. This is mostly related to clayey soil (higher RU) on these fields. Compared to farmers' strategies, the optimized irrigation scenario has the advantage to lower the average (AIM) and maximum (MIA) irrigation amounts for all fields, but also the total irrigation amount (TIA) where water was overused. It also lowers the total number of irrigation in most cases, but suggests much higher number of irrigation on sandy soils (P7, P8).

Table 4.5: Set of indicators to compare current fertigation strategies and the proposed optimized strategies: LDP: longest dry period in the 120 first days after transplantation, AIA= average irrigation amount, MIA = Maximum irrigation amount, MiIA = minimum irrigation amount, TIA = total irrigation amount, AIF = Average irrigation frequency, TNI = total number of irrigations; NDWS = number of days of water stress, NDNS = number of days of nitrogen stress. Bold: optimized strategy, non-bold: current farmer's strategy

	LDP		AIA		MIA		MiIA		TIA		AIF		TNID		NDWS		NDNS	
	d		mm		mm		mm		mm		d		d		d		d	
P1	**25**	8	**17**	94	**30**	174	**14**	16	**486**	2806	**5**	4	**29**	30	**0**	10	**0**	119
P2	**62**	20	**18**	43	**31**	97	**16**	10	**585**	1744	**7**	5	**32**	41	**0**	0	**0**	144
P3	**31**	9	**23**	52	**43**	138	**20**	8	**509**	1869	**7**	4	**22**	36	**0**	44	**0**	87
P4	**41**	17	**19**	28	**36**	50	**16**	9	**536**	756	**6**	6	**28**	27	**0**	0	**0**	72
P5	**33**	20	**16**	37	**24**	105	**14**	8	**579**	702	**4**	8	**36**	19	**0**	19	**1**	102
P6	**11**	11	**9**	23	**23**	39	**6**	8	**239**	565	**6**	6	**26**	25	**0**	25	**0**	9
P7	**9**	26	**7**	27	**14**	36	**4**	15	**600**	373	**3**	9	**90**	14	**0**	129	**3**	78
P8	**19**	23	**11**	60	**20**	150	**7**	15	**570**	1081	**3**	8	**54**	18	**0**	36	**1**	117
P9	**17**	36	**8**	15	**12**	52	**5**	2	**616**	262	**4**	10	**82**	17	**0**	83	**0**	72
P10	**15**	11	**9**	37	**23**	104	**6**	16	**231**	1549	**5**	3	**26**	42	**0**	12	**0**	68
P11	**15**	14	**9**	13	**23**	33	**6**	3	**249**	335	**5**	5	**28**	26	**0**	16	**0**	22

4.4 Discussion and conclusion

The aim of this paper was to describe through a modelling approach, the fertigation strategies implemented by farmers in the Merguellil downstream plain

and assess their agro-environmental impacts and drawbacks before testing alternative scenarios regarding irrigation scheduling and nitrogen applications to increase yields. Using a model such as Optirrig, whose parameters are not always transposable from a particular situation to another, requires to adapt calibration processes to such conditions. To achieve the goals of the study, we first tested the two different model calibration approaches. The findings showed that a deterministic trial-and-error calibration approach was less adequate to our case-study. Conversely, a multi-stage numerical approach that leans on model analysis techniques (sensitivity analysis, uncertainty analysis) appeared more relevant. These results are not generic meaning that another calibration approach might be more adapted depending on field conditions. However, our methodology aiming to test different calibration approaches to represent farmers' practices in poorly-gauged environment can be easily adjusted and adapted to other conditions.

The most important finding of this study was that, in this relatively small territory where farmers lean on the same water resources and are affected by similar constraints, the fertilization strategies they currently implemented for chili-pepper cropping generally generate massive water drainage and nitrate leaching. The results also suggest that water supply is not efficiently distributed over time resulting in frequent crop water and/or nitrogen stresses. Farmers' strategies might be affected by potential arbitrage between crops for water. Indeed, when other crops are conducted in the same period, farmers might tend to prioritize one crop to another. A possible explanation of the high amounts (described in here by a set of indicators of irrigation doses), is that, considering irrigation can be particularly time consuming for these farmers, they might decide to provide high amounts of water relatively distant in time, instead of reduced but and more frequent applications as suggested by the optimized scenario generated as pathway of improvement. A similar pattern of results was obtained by Laib et al. (2018) in greenhouse irrigated horticulture in the Algerian Sahara. Alternatively, the high amount of irrigation applied might also be explained by the fact that irrigation is quantified in terms of duration and not in terms of supplied water volume per plant by the farmers. Indeed, as noted during the surveys, to define these durations, farmers took into account their pumping capacity, which they consider to define the water flow. For some of them, the lower the horse vapor is, the less the flow is delivered, and the longer should they irrigate. This led to long irrigation durations. Another explanation highlighted by Venot et al. (2017) might be the fact that farmers did not adapt their strategies to the drip irrigation technique and continue to pump water like in furrow irrigation. Furthermore, we showed that substantial water and nitrogen savings and consequently yield gain were possible in most cases by adopting an

optimized irrigation strategy. Fertigation practices on a limited number of plots appeared close to optimal, meaning that no significant yield improvement was simulated, and relatively few water saving was possible. Further investigation on these strategies might be interesting to understand the factors driving them. For local agricultural and water management stakeholders, understanding and promoting such strategies adapted to farmers' socio-economic and pedoclimatic conditions, might be a first step toward an increase of water and nutrient use efficiency at the territorial scale.

Chapter 5

Towards an improvement of drip irrigated market gardening systems through agroecological practices

5.1 Introduction

In Chapter 2, a high level of diversity was found concerning technical operations (TOs) and the resulting management routes for chili-pepper-based cropping systems in the Merguellil plain, leading to the description of seven characteristic TMRs. Within these, interesting agroecology-compatible practices were identified. These, however, were not specific to one type of TMR but rather spread within the management routes. The analysis further showed that the TMRs considered as a whole could be ranged from more intensive (input-wise) to more environmental-friendly. Two limits of the analyses pertain to the fact that i) the environmental impact of the whole TMR was not quantitatively assessed, ii) an economic evaluation of these TMRs was not undertaken. Chapters 3 and 4 monitor and model the water and nitrogen budgets and the resulting yield of plots representative of these different clusters. The resulting agro-environmental performances were also very diversified. This chapter seeks to undertake an integrative analysis of optimization strategies of the cropping systems concerning the water, nitrogen resources and yield components. As such, it explores beyond results in Chapter 4 on improved efficiencies through optimization of the irrigation scheduling and/or the integration of representative agroecological practices observed in the region in the studied crop systems. This seeks to answer the following question: can the implementation of locally widespread

agroecological practices improve irrigation performances, regarding productivity and water and nitrogen use efficiencies? Indeed, it is known that agroecological practices, such as agroforestry, can improve productivity and efficiency in irrigated systems in Northern Africa (see, among others, Temani et al. (2021)). Most scientific analyses are however undertaken in experimental conditions, in which irrigation management is adapted to the observed agrosystem, bringing near to optimal amounts. The analyses then reside in whether this water is better used in mixed cropping systems rather than monospecific systems. In practice, it has been shown that farmers in the Southern Mediterranean do not necessarily adapt irrigation management to the cropping system (Venot et al., 2017). Learning processes on drip irrigation management can indeed be long, with some farmers still implementing management options adapted to surface irrigation (not frequent, long applications) rather than to drip systems (frequent, short applications). Thus, should the performances' (yield, drainage, nitrate leaching, income) improvement reside solely on improved management and/or could alternatives to chemical fertilizers (substitution solutions) and/or a (partial) redesign of the cropping system be part of the solution? For instance, organic fertilization (through the use of manure tea (MT)) and crop associations (such as olive trees - vegetables agroforestry) are two agroecological management practices that enable production with fewer external inputs or limited environmental impacts (Altieri, 2002) and have the potential to optimize land and water uses and productivity in horticultural production (Álvarez-Solís et al., 2016). These practices are widely adopted in the Merguellil downstream plain as shown by (Ameur et al., 2020). But their real impact on the productivity and profitability within drip irrigation systems and their environmental sustainability are little known. As such, for the objective of this final chapter, we propose to test the agronomic, environmental and economic interests of the implementation of a set of practices (optimized irrigation strategy, manure tea and agroforestry) to improve drip irrigation performance. This exploratory analysis is based on the data collected on the eleven fields involved in the previous chapter (3 and 4). These are referred to, using the same naming (P1 to P11). The analysis is undertaken on the basis of a comparison of scenarios using a set of hypotheses. Note that the scenarios were not thoroughly tested experimentally but the analysis opens perspectives for further researches.

5.2 Practices to improve the performances of the studied systems

In chapter 4, we found that the performances could be substantially improved through optimized fertigation strategies. To test whether further improvements

could take place through the implementation of agroecological practices, we estimate the potential effects of an optimized irrigation strategy, the use of manure tea and agroforestry on several components of agri-environmental and socio-economic dimensions (described in the next section). Numerous agroecological practices have been identified in the Merguellil downstream plain (Ameur et al., 2020): relay intercropping, agroforestry, diversification, livestock integration, use of manure tea, integration of legumes in crop successions, etc. The use of manure tea and agroforestry (Figure 5.1) were chosen as these are widely implemented in chili-pepper cropping systems and are receiving increasing interest from farmers. This choice is also justified by the fact that the adoption of these two practices is mainly facilitated by drip irrigation technology. They appear promising, provide a lot of services as described below and lend well to assess the complementarity between drip irrigation and agroecological practices. During the 2019 field monitoring, MT was used on three fields out of the eleven monitored (P1, P2, P5). Three other plots were agroforestry systems (P4, P7, P10). Their were no use of MT nor agroforestry systems on the other fields (P3, P6, P8, P9, P11). We investigated the use of MT during the field surveys. In addition, an experimental design was set up on a separate field [1] (not included in the eleven sampled fields) to monitor the water sharing between olive trees and chili-pepper.



Figure 5.1: Some agroecology-compatible practices in Tunisia (Ameur et al., 2020): (a) liquid manure production basin; (b) pepper-olive grove agroforestry system

[1] This field was not included in the final sample as the monitoring was not completed due to pest attacks and massive chili-pepper plant transplantation failure

5.2.1 Manure tea

Manure tea (MT) organic fertilization is a well-known and adopted practice of synthetic fertilizer substitution solution in the Merguellil downstream plain. MTs, produced through an anaerobic fermentation process, are aqueous extracts produced by dipping bags of manure in water (often for a couple of days). The process is similar to compost tea production processes described by Zaccardelli et al. (2018). The latter have high contents of nutrients, humic substances and micro-organisms. Studies on these compost teas have shown multiple benefits on plants, including improved growth and yield (Siddiqui et al., 2008; Pane et al., 2014, 2015). Further, Dugué et al. (2014) note the use of MTs in the Moroccan context, while Ameur et al. (2020) describe its widespread use in three irrigated plains in North Africa. Specifically, these authors noted a downward trend in the use of commercial liquid organic fertilizers and the increased use of manure tea in the Merguellil downstream plain. Indeed, the production and use of MT was triggered by the arrival of commercial liquid organic fertilizers. It is a homemade solution of substitution to these expensive commercial liquid organic fertilizers. Farmers usually use about 200 $L.ha^{-1}$ of MT, with a nitrate concentration of approximately 20 $mg.L^{-1}$ (Leauthaud et al., unpublished data). MT is generally used in green market gardening, to produce crops such as chili-pepper, tomato, melon and watermelon.

5.2.2 Agroforestry

Agroforestry systems are also widespread in the Merguellil downstream plain, especially olive grove agroforestry systems. Even though these systems provide numerous economic and environmental benefits, there is a gap in scientific literature concerning profitability and efficiency of irrigated olive grove agroforestry with vegetable crops in the Southern Mediterranean region, as mentioned by Leauthaud et al. (2021). However, Temani et al. (2021) showed these systems can improve land productivity compared to sole crops and trees, even under arid conditions. Karray et al. (2008) for their part, have described water sharing in these systems in Central Tunisia. In the Merguellil downstream plain, more than 90% of farmers had an olive grove in 2015 (Azizi, 2018). There was an increase of its association with fruit trees, vegetable crops or cereals between 2005 and 2015. Olive grove vegetables agroforestry for instance increased from 5% to 9% (Azizi, 2018). Commonly, farmers adopt this practice as a strategy of intensive cultivation to reduced input consumption. These systems also emerge from contractual arrangements between farmers with different land, water and workforce assets (Leauthaud et al., 2021). A field monitoring of soil water content was realized in 2019 in a 10m*20m agroforestry system (Figure 5.2). Soil water potential was monitored at three different depths (15cm, 30cm, 45cm) along two

transects, with measurements at 90cm at some points. The monitoring revealed that i) trees were susceptible to extract water along the whole transect, including at the center of the inter-row, showing that olive tree roots extended to at least 10m (Figure 5.3) and ii) due to regular soil tillage, olive tree roots were restricted to the lower part of the soil (under approximately 45 cm in depth), while annual crop roots were mainly concentrated within the upper 45cm of the soil. Hence, no evident interactions existed between the roots of these two spaces.



Figure 5.2: Olive tree chili-pepper agroforestry system monitoring experimental set up, 2019. (Credit: K. Akakpo, 2019)

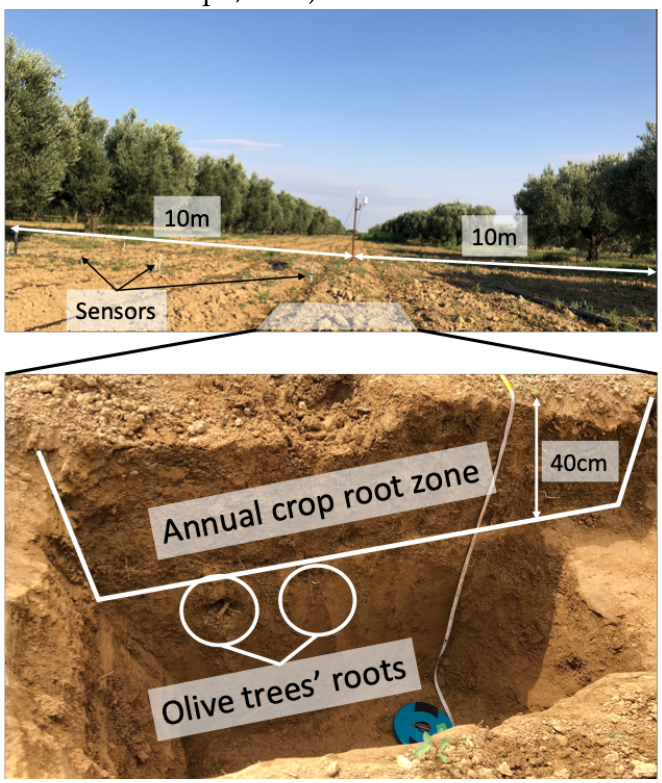


Figure 5.3: Olive trees and annual crop roots zones exploration. The pit was realized at the center of olive trees inter-row (Credit: K. Akakpo, 2019).

5.2.3 Irrigation management

Farmers' irrigation management practices were described in Chapter 3 (Section 3.3.3) and Chapter 4. As a reminder, two strategies were identified. On the one hand there were strategies aiming to regularly provide water to plants. On the other hand, there was strategies comprising two irrigation phases, separated by a relatively long dry period, of up to thirty days. Both strategies generated massive drainage and nitrate leaching as simulated in Chapter 4. Thus, we do not distinguish these strategies in this analysis, and each farmer's irrigation practice is referred to as "current strategies". The optimized irrigation scheduling generated for each field in chapter 4 to limit drainage are referred to as "optimized irrigation strategy". Both "current strategies" and "optimized irrigation strategies" were described in the previous chapter through a set of indicators.

5.3 Scenario hypotheses and assumptions

5.3.1 Scenarios

Four scenarios of management are tested and include three optimized practices: optimized irrigation scheduling, the use of manure tea (MT) within olive grove-chili chili-pepper agroforestry systems, and the combination of all these. For each scenario we compute a set of variables related to the agri-environmental and socioeconomic dimensions, represented by water and nitrogen budgets (inputs, drainage and nitrate leaching), total yield and economic data (water, energy, fertilizer and labor costs, revenues and workload). The scenarios are described below.

- Non-optimized situation (NOS): *Current practices*.

  In this scenario, management rules as implemented by each farmer during the 2019 growth season and the resulting water and nitrogen budgets and yield are considered. For each field, this scenario is considered as the reference to which the optimized scenarios are compared. Water and nitrogen inputs are equal to the measured amounts, simulated drainage and nitrate leaching presented in chapter 4.

- Scenario 1 (S1): *Optimized irrigation strategy*

  In this scenario, all technical operations remain unchanged, except irrigation strategies. The farmers' strategies are replaced by the optimized ones concerning dates and doses of irrigation applied to the crop. Irrigation water supply is basically equal to chili-pepper water requirements. The dates

and doses were generated through the optimization process implemented in chapter 4.

- Scenario 2 (S2): *Agroecological system*

  In this scenario, all chili-pepper fields are considered in association with olive trees, to form an agroforestry system. The current practices of each farmer, as in current practices, are applied and where relevant, it is assumed that the farmer further uses manure tea, without modifying other technical operations. We assumed a same planting density for all plots (100 trees per hectare, with a spacing of 10m*10m).

- Scenario 3 (S3): *Water optimized agroecological system*.

  This strategy combines the two previous scenarios: Scenario 1 and 2. It is assumed that chili-pepper is grown in an agroforestry system, in which MT is used in addition to the other technical operations originally implemented by the farmers. The irrigation doses and dates are those used in scenario 1 (generated in chapter 4) plus olive trees water requirement.

For each scenario, some hypotheses and assumptions were made to determine the different variables (water input, drainage, nitrate leaching, yield and income and some additional socioeconomic variables). The formula used to compute these variables for each scenario are presented in Table 5.1.

5.3.2 Water and nitrogen budgets

A simplified water balance equation was used:

$$I + P - ET - D - \delta S = 0 \tag{5.1}$$

where I = Irrigation amount, P = Rainfall, ET = evapotranspiration (crop water demand), D = Drainage, δS = residual stock.

To simplify calculations, δS was set to 0. We assumed that crops' water requirements were solely provided by irrigation, hence P was also set to 0. In mono-species scenarios (NOS and S1), ET is equal chili-pepper water demand. In agroforestry scenarios (S2 and S4), it is equal to both chili-pepper and olive trees water demand. Hence, for any given scenario, equation 5.1 becomes:

$$I - ET_P - ET_O - D = 0 \tag{5.2}$$

where ET_P = chili-pepper water demand and ET_O = olive trees water demand (if applicable; if not, ET_O = 0). Olive tree water demand was set 600 mm (FAO, 2021).

The functioning of agroforestry systems (Scenarios 3 and 4) is hard to represent due to the large number of interactions taking place between species concerning light, water and nitrogen uses. Both competition and facilitation interactions can exist depending on conditions (He et al., 2013). In hot conditions, trees can improve crops' growing conditions by providing shade. But the decrease in received radiation under olive trees for annual crop, can be limiting for evapotranspiration in other conditions. We did not analyze all the interactions within agroforestry systems for this study. Based on monitoring described in section 5.2.2, water and nitrogen sharing principle in agroforestry systems is simplified as follow:

- no interactions exist between the two species root systems and water and nutrient are primarily supplied to chili-pepper.
- olive trees uptake water and nitrogen from deep horizons, below the chili-pepper root zone. Hence, drained water and leached nitrate from the chili-pepper root zone can be used by olive trees.

For all scenarios, nitrogen input amounts were maintained similar to NOS. To compute the nitrogen budget in agroforestry scenarios, we set the nitrogen uptake of olive trees to 45 $kg.ha^{-1}$ (Fernández-Escobar, 2011) although various amounts are proposed in the literature. Nitrogen supply of MT was negligible (see section 5.2.1).

5.3.3 Yield components

The presence of trees within the agroforestry system reduces the planting area of the annual crop. Considering a typical field structure of an agroforestry system (10x10m rows for olive trees, chili-pepper intercropped at a 1.5 m distance from trees and row distances of 1.2 m), chili-pepper yield decrease due to the direct decrease of planted area (and eventually other competition interaction, e.g. for light) was considered to be 20%[2]. Olive yield was set to 50 kg per tree (5 $T.ha^{-1}$ on average) (Morel 2018 unpublished report, FAO, 2021).

Previous studies have shown that use of compost teas results in increased yields (Álvarez-Solís et al., 2016), approximately by 20% (Zaccardelli et al., 2018). Hence in the Scenario 3, the use of MT compensates the decrease due to crop association, leading to a 0 increase in yield compared to reference situation for chili-pepper. For farmers already using MT (P1, P2, P5) or fields already in agroforestry (P4, P7, P10), a 20% decrease or in increase in yield was applied. To determine the interest of each scenario, we computed a ratio as follows for the

[2]Value set arbitrary. Temani et al., 2021 estimated this decrease to 50% for faba been and wheat in rain-fed conditions.

Table 5.1: Methods used to estimate each variable for all scenarios. For agroecological (S3) and water optimized agroecological (S4) systems, the estimation of yield differs depending on whether the field was originally an agroforestry system or manure tea was used or not. Rows concerning fields where MT was used in the reference situation are overlaid in brown. Rows concerning agroforestry fields in reference situation are overlaid in green olive. I: Measured irrigation amount in farmers' current practices; D: simulated drainage in current practices; N_{lix}: simulated nitrate leaching in current practices; Y_{obs}: Observed yield (measured during 2019 field monitoring); Y_{sim}: simulated yield for the optimized irrigation strategy (simulated in Chapter 4).

Scenario	Fields	Irrigation	Drainage	N leaching	Yield
S1	P1 to P11	I	D	N_{lix}	Y_{obs}
S2	P1 to P11	Sim	0	0	Y_{sim}
S3	P1, P2, P5	I	D - 600	N_{lix} -45	Y_{obs}*0.8
S3	P4, P7, P10	I	D - 600	N_{lix}-45	Y_{obs}*1.2
S3	P3, P6, P6, P10	I	D - 600	N_{lix}-45	Y_{obs}*0.8
S4	P1, P2, P5	Sim + 600	0	0	Y_{sim} * 0.8
S4	P4, P7, P10	Sim + 600	0	0	Y_{sim} * 1.2
S4	P3, P6, P6, P10	Sim + 600	0	0	Y_{sim}

chili pepper crop:

$$YieldRatio = \frac{Senaiorio'sYield - Y_obs}{Y_obs} \tag{5.3}$$

A Yield ratio > 0 suggests that production in the scenario is higher than that of the reference situation (current practices). Ratio of 0 indicates no effect and ratio < 0 indicates lower production. In agroforestry scenarios, the ratio can be interpreted as a land equivalent ratio (LER) of the annual crop, which is the ratio between its yield in an agroforestry system in comparison to its yield in a mono-culture over the same period.

5.3.4 Gross revenue and other socio-economic variables

Gross revenue was calculated by multiplying the total marketable yield harvested by an average price of 1 $TND.kg^{-1}$ for chili-pepper and 1.3 $TND.kg^{-1}$ for olive (Morel 2018, unpublished report). This is a simplistic approach as prices substantially vary during the season. Further, field monitoring involved a partial acquisition of economic data and workload. The current analysis hence draws from this local knowledge – rather qualitative in nature –, completed by a set of hypotheses. Energy use and costs were variable and depended on energy sources. Labor costs also varied depending on the type of activity, while fertilizer costs depended on the commercial form of the products used. Thus, three levels of effects of scenarios on water/energy, labor, and fertilizer costs, and working time were defined: substantial decrease (- - -), negligible effect (NE),

substantial increase (+++). A substantial decrease in input amounts generated substantial decreases in costs and vice versa. The number of days of irrigation (Table 4.5) was used to estimate the impact of irrigation on workload. We considered that the farmers themselves managed irrigation activity, as observed in all the monitored fields, even though it was sometimes realized by a third party. So, irrigation and the use of MT had a negligible effect on labor costs. Additional costs existed in the case of yield increases (increasing harvesting time) and olive tree pruning. These also generated additional workload for the employees.

These effects can be synthesized as follow. In the initial situation (IS), For any given scenario

- Water and energy cost

  Irrigation amount > 1.2 * Irrigation amount in NOS ⇒ Substantial increase in water and energy cost (+++)
  Irrigation amount < 0.8 * Irrigation amount in NOS ⇒ Substantial decrease in water and energy cost (- - -)
  0.8 * Irrigation amount in NOS < Irrigation amount < 1.2 Irrigation amount in NOS ⇒ negligible effect (NE) on water and energy cost (NE).

- Labor cost
  Irrigation has no first order effect on labor cost as farmers themselves are involved in that activity. Olive trees pruning was assumed to have a negligible effect on labor cost. An increase in yield generates substantial increase in labor cost and inversely.

- Workload
  Increase yield NOS and/or in the number of days of irrigation ⇒ substantial increase workload (+++)
  Decrease yield NOS and in the number of days of irrigation ⇒ Substantial decrease in workload (- - -)
  Yield = Yield in NOS ⇒ negligible effect on workload

5.4 Results

In addition to the optimization through irrigation management, this chapter seeks to assess whether further improvements could be realized through the implementation of agroecological practices. The most important information resulting from the analyses is that all three improvement scenarios tested have agro-environmental and economic interests, but also limits. They can potentially contribute to better performances regarding agro-environmental variables but less interesting economically for some farmers. For other, they might enable to

reduce the environmental impacts (water withdrawals, drainage, nitrate leaching) while increasing productivity and eventually income. In most of cases, the three scenarios were more productive and/or profitable than the *current practices*.

5.4.1 Water and nitrogen budgets

Figures 5.4 and 5.5 represent the quantitative variables. A table of both qualitative and quantitative variables is presented in appendix. On both figures, the variables were normalized to range between 0 and 1. The charts are grouped according to clusters (obtained in chapter 2). We note that all three scenarios might allow to reduce/limit water drainage but also nitrate leaching in all fields. Indeed, with an optimized irrigation strategy (S2 or S4), the required amount of water is applied, resulting in limited drainage. In agroforestry scenarios, the olive tree root system enables a recycling of resources drained from the chili-pepper root zone. However, in the cases where relatively limited amounts of water are applied by farmers in reference situation, additional irrigation is required to cover both species requirements in agroforestry systems (S3 and S4), e.g. P7 and P9. We also note that the proportions of savings (water and nitrogen) vary depending on fields, and more importantly between the fields of a same cluster (P1 and P6 of cluster 1 for example).

5.4.2 Yield components

As simulated in the previous chapter, S1 might generate higher productivities than reference situation in most cases. S2 might also higher yields in some cases, especially in field already in agroforestry, due to the use of MT. It should be less interesting regarding yield for P1, P2 and P5 as these already integrate the use of MT. Indeed, association with olive trees with same management rules implemented by these farmers substantially decreased yield due to lower cultivated area for chili-pepper (P1, P2, P5) and competition interactions. However, the "Ratio" for olive tree or the land equivalent ratio of the whole system might be higher, as far as fertigation enables “higher production of olive in agroforestry systems, compared to mono-culture” according to farmers. Hence, the loss in chili-pepper might somehow be compensated by the olive trees. Further, note that no substantial changes in yield might exist in S1, S2, and S3, if the realized yield in S1 is close to the optimum as for P6 and P11, but additional revenue could be generated true agroforestry.

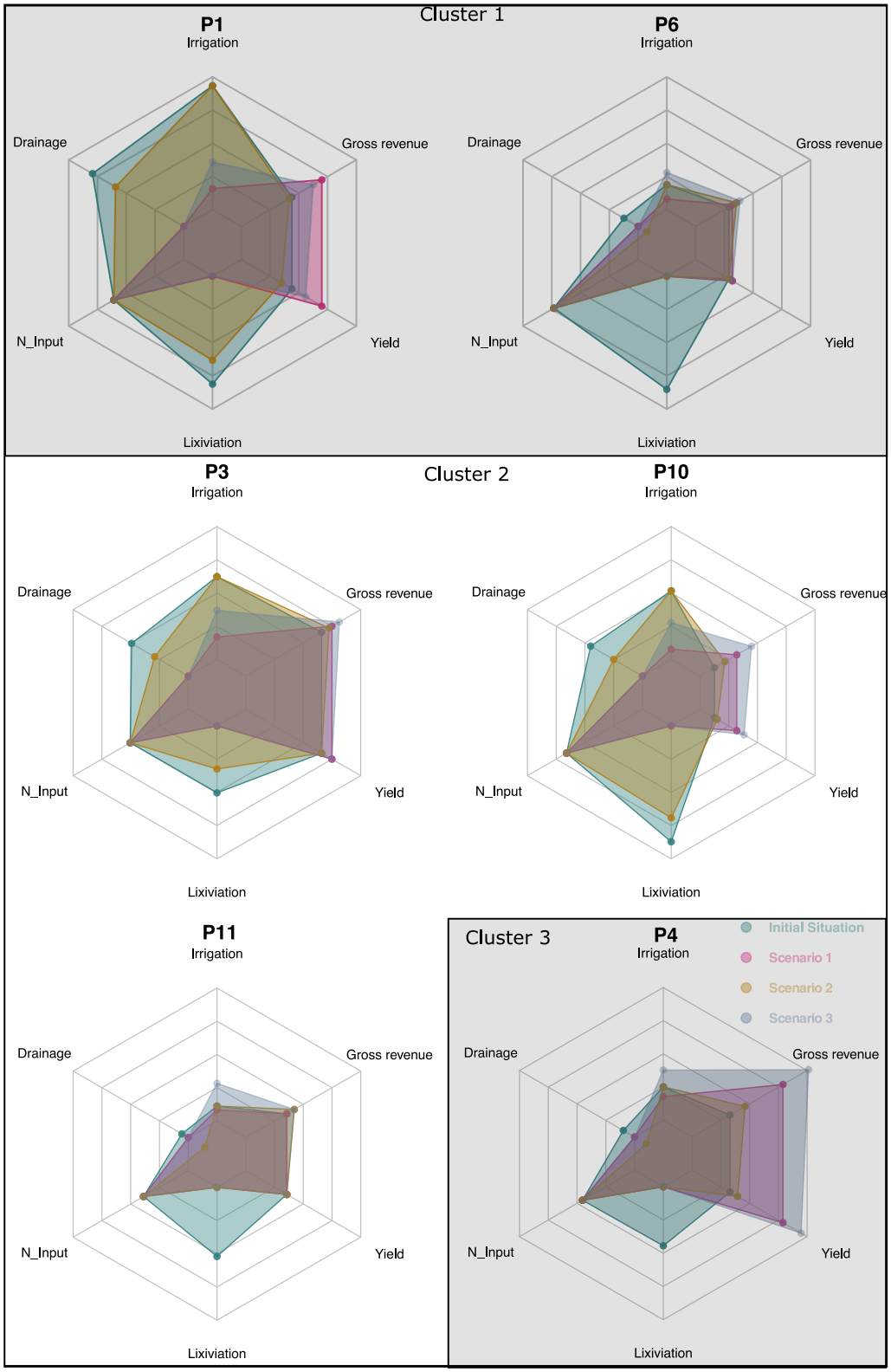


Figure 5.4: Agro-environmental variable and socio-economic variables (P1 to P6)

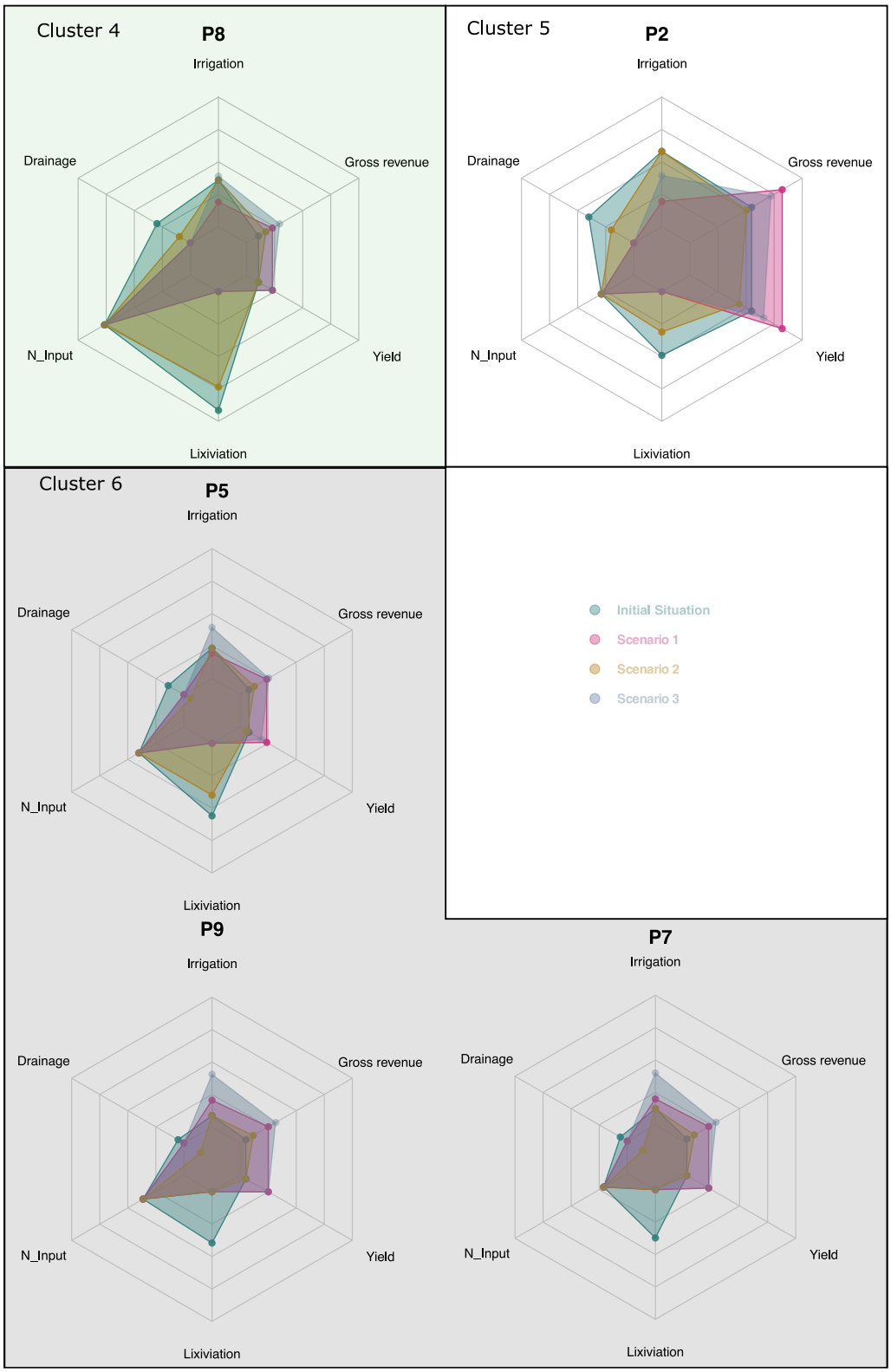


Figure 5.5: Agro-environmental variable and socio-economic variables (P1 to P6)

5.4.3 Socio-economic impacts

On the economic dimension, S1 might enable substantial reduction of water costs in case of over-irrigation in current practices (P1, P2, P3 and P10). Inversely, it can generate additional costs if crops water requirements were not met. These costs would be even more significant in an agroforestry system (S3) to meet olive tree demands. But actually, farmers do not take into account olive trees' requirements to design annual crop managements rules. Unless further increases in yields are not possible, the scenarios we propose generate additional working time and labor cost, related to additional harvests, manure purchase or olive tree pruning. However, these costs are counter-weighed by additional income. In addition, S1 and S3 can be very time consuming and binding. Indeed, the number of irrigation days (see Table 4.5, Chapter 4) can double with the optimized irrigation strategy. For example, it would rise by a factor of 5 to 6, respectively for P9 and P7. This increase related to the optimization process was due to the need to irrigate more often on draining sandy soils.

Furthermore, concerning economic data, the revenue is an interesting indicator to compare scenarios as well as systems, even if it is not the most relevant one. In general, the scenarios we propose generate substantial increase in revenues consecutive to increases in yield. However, revenue varies considerably depending on scenarios, fields and even clusters. For example, S1 could almost double income of P1 whereas S3 could lower it by about 20%. For the same field, S2 would have generated higher income than current practices but lower S3. These conclusions are valid for all fields already using MT like P1. In the other cases, S1 gives higher income coming from increased yield. S2 and S3 might produce additional income from olives.

To sum up, Water optimized agroecological system (S3) appears as an interesting trade-off to at least the current production systems, by both reducing resource wastage and generating additional income for some farmers (P1, P2, P3, P4, P10). Although it can increase revenue, the use of MT combined with agroforestry (scenario 2) in the current practices offers marginal environmental interest regarding the current fertigation strategies. Environmentally, S1 is the ideal alternative, but its implementation (as S3) could be binding.

5.5 Discussion and conclusion

This chapter sought out to answer questions of a possible improvement of fertigation performances, regarding productivity and water and nitrogen use efficiencies through the implementation of locally widespread agroecological practices. The three alternative scenarios tested in the analyses revealed agro-environmental and economic interests, but also limits. We found that alternative

scenarios can be environmentally viable but less interesting economically for some farmers and inversely for others.

As described previously, there is an evident scope for improvement in most of the fields. The pathways of improvements, whether through optimized irrigation on agroecological practices, depend on the specific context of each plot, and must therefore be analyzed on a case-by-case basis. Hence, their is no generic scenario of improvement and each farmer's case should be handled separately. However, as a first of action at territorial scale, the improvement of resource use efficiency and yields is primarily achievable through better management of irrigation, and for systems that manage their inputs (water and nitrogen) well, through the implementation of agroecological practices. Irrigation, on the other hand, generates additional work, which is not always compatible with the farmers' work schedule.

These conclusions must be taken with caution. The increases in yield and revenue presented are hypothetical and correspond to an actually cultivated area of one hectare. In the practice, the yield per surface might be inferior as the actually cultivated area on a field are often largely inferior to the field area. We are aware that the analyses presented in the section can appear speculative. However, the observed and hypothetical marketable yields presented tie well with observed yields. Another limitation of this work is the absence of experimental data to support the findings. In-depth multicultural analysis might be undertaken to confirm the conclusions. Nonetheless, based on the simplistic assumptions we made, we showed that agroecological practices are an interesting path to improve sustainability of drip irrigation agriculture in the Merguellil downstream plain. However their implementation within the current practices might not solely lead to better efficiency, productivity and profitability. Adapting fertigation strategies and combining them with agroecological practices seems more promising although challenging. The analyses confirm the importance to adapt agroecological practices to local conditions and farmers' contexts. This preliminary investigation goes somehow against previous literature on the subject (Wezel, 2017) stating that agroecological practices can substantially improve performances of drip irrigation. However, the findings are supported by the ESR framework (Hill, 1998) which emphases the upgrade of practices and efficiency increase as first of agroecological transition process.

Finally, one can rightly wonder about the interest for a farmer to switch to an agroforestry system in return for a reduced yield. Hence the interest to evaluate the total profitability of the system. The main limit of this approach is that it does not analyze the gross margin, which better reflects the profitability. Nevertheless, this exploratory analysis gives a concrete vision of the possibilities offered by agroecology to improve drip irrigation performance.

Chapter 6

General discussion and conclusion

This final chapter aims at:

- analyzing the robustness of the conclusions, in methodological and result terms, by comparing the analyses provided by the different but complementary approaches used in this research: the description of the diverse technical management routes applied to chili-pepper-based crop systems and their qualitative assessment (chapter 2), the quantitative assessment of the environmental impacts of these TMRs (chapter 4) and the analysis scenarios of improvement of practices (Chapter 5),
- discussing the global methodological approach,
- presenting the limits of the study and perspectives of future research actions on the subject.

Starting from the postulate that, despite its limits, drip irrigation could become a lever of action towards the agroecological management of crops in the Southern Mediterranean context and more generally within Mediterranean or semi-arid climates, this thesis analyzes this technology in a broader perspective, considering it as a potential vector of interesting practices, that could contribute to initiate a transition towards more sustainable cropping systems. Table 6.1 summarizes the problematic and objectives of the thesis. The methodology used to treat each question and the key findings are synthesized on Figure 6.1.

6.1 Summary of results

As the overall goal, this thesis aimed at analyzing whether locally existing agroecological practices can be a lever of action to improve the performances of drip irrigation technology.

Table 6.1: Research questions and objectives

Questions	
How can agroecology be integrated into the understanding of irrigated systems using drip irrigation? Is the implementation of agroecological practices in these systems a solution to improve resource use efficiency and address environmental issues?	
General objective	Specific objectives
Analyze the conditions in which locally existing agroecological practices, integrated within technical management routes applied by farmers, can be a lever to improve performances of drip irrigation technology.	A thorough and methodic description of the diversity of farming technical management routes (TMRs) for a representative crop. An assessment of the environmental impacts of these diverse technical management routes, using both qualitative and quantitative approaches. The analysis of improvement pathways regarding irrigation performance, through the dual integration of agroecological practices and new patterns of irrigation scheduling.

Through a thorough description of the diversity of farming technical management routes (TMRs) on a sample of 45 plots, and their qualitative assessment, this work first showed that highly contrasted TMRs existed within the study zone, despite its relatively limited size and similarities in farmers' technical and socio-economic conditions (chapter 2). Seven typical TMRs were found, with a gradient ranging from non-environmental-friendly to more environmental-friendly ones. This qualitative assessment of environmental impacts is however not straightforward as identified TMRs were constituted of various technical operations each integrating more or less sustainable practices. On the one hand, several practices presented in the literature as agroecology-compatible (Wezel et al., 2014; Ameur et al., 2020) were identified within these TMRs, including the use and conservation of local chili-pepper varieties, relay cropping, tree-annual crop associations, cucurbitaceae or leguminous, integrated crop-livestock systems which enabled crop residue grazing or organic fertilization. On the other hand, the TMRs were combinations of these agroecology-compatible practices with less virtuous practices such as high level of pest management product application or high levels of fertilization. Hence, we demonstrate that the drip irrigation technology contributes to diversify farming practices, by enabling the

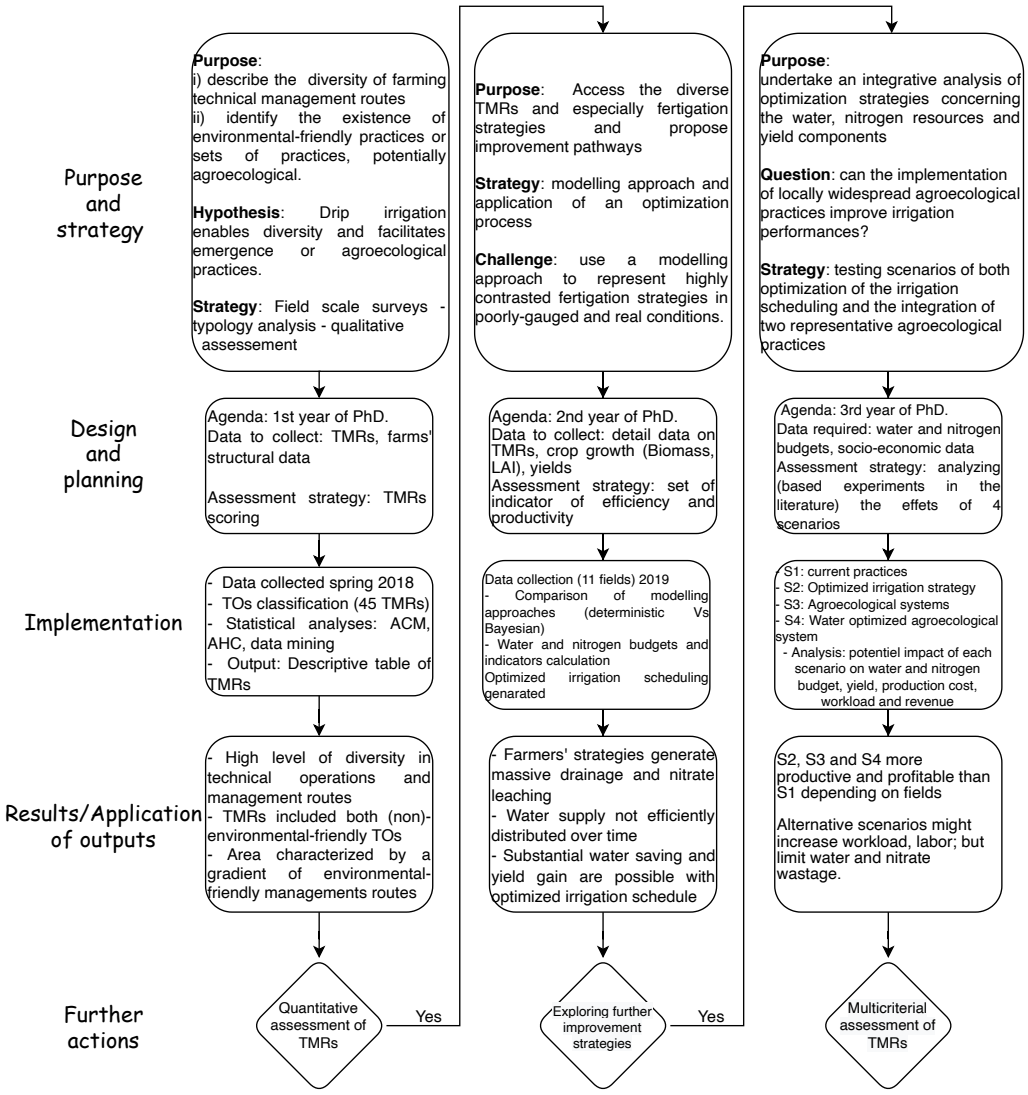


Figure 6.1: Synthesis of the thesis: implementation of the Bos et al. (2004)'s conceptual framework to each specific objective.

implementation of a wide range range technical operations, TMRs and crop systems. Agroecology-compatible practices within these systems are embedded in farms with a combination of other practices, with the aim of improving the economic return of the systems. Hence, from these diverse TMRs, however implemented in farming systems thought with a non-agroecological perspective, one can ask two questions:

- could interesting management options that conciliate production, and hence the economic return, and environmental issues already exist within these TMRs? This tracking is interesting as these systems could constitute both locally adapted and adopted and more virtuous cultivation options;

- to what extent the agroecological practices characterized within the TMRs can be a solution to improve the current cropping systems?

Answers (synthesized in figure 6.1) are provided to these questions hereafter, focusing specifically on water and nitrogen resources. With the quantitative assessment undertaken on a limited number of 11 representative fields (chapters 3 and 4), we have shown that, in general, most farmers' fertigation strategies generate massive drainage and nitrate leaching. However, some farmers' strategies allow to achieve relatively low amounts of drainage and nitrate leaching. We also found that the management of fertigation could be improved to reduce impacts of water losses and limit pollutant transfer towards the aquifer. We evaluated this potential of improvement and found that substantial water and fertilizers savings were possible resulting in significant yield gain in most cases.

In addition, a cross-analysis of findings of both qualitative and quantitative assessments enables to state that, in general, i) non-environmental-friendly TMRs led to high yield; inversely, ii) environmental-friendly TMRs generated lower yields; iii) some environmental-friendly TMRs, were as productive as non-environmental-friendly TMRs. Indeed, fields representing cluster 1 and 2 - non-environmental-friendly TMRs (Chapter 2) - were the most productive (29 to 66 $T.ha^{-1}$ in marketable yield). Most environmental-friendly TMRs of cluster 6 were less productive (8 $T.ha^{-1}$ maximum). Amidst these yields generated by both (non)-environmental-friendly TMRs, intermediary TMRs have generated intermediary yields (10 to 33 $T.ha^{-1}$). Nonetheless, P2 (cluster 5) and P10 (cluster 2), which unlike the other fields within the same category ((non)-environmental-friendly), generated respectively high and low yields. Hence, even though TMRs play a key role, yields are highly linked to the variety used, as expressed by farmers: "hybrid varieties are far more productive than local varieties." So, the varietal choices play a crucial role in productivity, but the farmer does not always adapt his management to this parameter. The results tie well with previous works wherein yield was estimated to about 70 $T.ha^{-1}$ for the hybrid variety and 12 $T.ha^{-1}$ for the local variety (Morel 2018, unpublished report). Considering the whole TMR, despite some limits, partly related to non-optimum fertigation strategies, we found that there are TMRs adapted to both varieties, as illustrated by P2, allowing to relatively high productivities and efficiency (P2 presented the highest NUE Figure 6.2)

Finally, we found that the performance of the studied systems can be substantially improved through the dual integration of agroecological practices (manure tea and agroforestry) and optimized patterns of irrigation scheduling. Although the adoption of these alternative solutions can generate additional income, they might also create additional production costs and workload depending on cases. These improvements pathways should be adapted to each farmer's

Qualitatitative assessment		Plots	Number of pesticide applications		N input kg/ha		WP kg/ha/mm	NUE kg/kg N	Yield kg/ha
			2018	2019	2018	2019	2019	2019	2019
Non-environmental-friendly	Cluster 1	P1	8	3	110	152	1.4	18.9	44
		P6	12	13	105	183	4.1	11.1	29
	Cluster 2	P3	5	4	152.5	126	3	31.9	66
		P10	12	12	177	165	0.7	5.1	12.6
		P11	8	8	166	97	7.8	20.8	35.7
Intermediary	Cluster 3	P4	3	3	102	113	3.5	19	33
	Cluster 4	P8	2	0	288	191	1.5	7	10.7
Environmental-friendly	Cluster 5	P2	4	3	40	72	2.7	38	55
	Cluster 6	P5	1	2	129	100	1.6	8.3	8
		P7	2	0	121	52.5	1.1	4.7	3.16
		P9	0	0	104	91	2.3	5.8	5.2

Figure 6.2: Synthesis of results and key variables and indicators describing TMRs.

conditions.

6.1.1 Contribution of the thesis

The contribution of the thesis are threefold. A generic and conceptual contribution lies in the overcoming of the apparent antagonism between agroecological practices and irrigated agriculture. Looking back at the problematic, objectives and recommendations for the research agenda concerning drip irrigation, presented in Chapter 1, the thesis' contribution to knowledge are declined in both findings and methodological approaches.

6.1.2 Contribution to knowledge

This thesis highlights four major points.

1. In real conditions, technical management routes applied to one crop system can be highly diverse. They are often a combination of diverse farming practices, involving both agroecology-compatible and conventional (chemically intensive) practices.

2. Crop management is evidently conducted to lead to good economic returns, but the farmer's profile plays a crucial role in the final applied management rules. This is reflected in both the applied TMRs and variety choices, and the structure of the farm: some seeking to maximize profit on rental land, while others seek to combine economic profitability with soil conservation on land they own.

3. Under farmers' conditions, and in most cases, irrigation scheduling of drip-irrigated market gardening crops (based on the analysis of chili-pepper cultivation practices) at the plot scale is highly inefficient. Substantial increases in efficiencies should be realized to achieve the high performances

sought with the use of drip irrigation. Locally, there is an evident potential of improvement of irrigation performance, in both economic and environmental terms.

4. Improvement pathways of drip-irrigated market gardening systems can involve optimized irrigation scheduling, but could also be accomplished through the integration of agroecological practices. These technical and system-level improvements are complementary, in the sense that they impact different dimensions of sustainability (socio-economic, agronomic, environmental), thus contributing to improve both resource use and the economic interest.

Through our research approach involving directly farmers as suggested by Benouniche et al. (2014), this thesis suggests a possible compatibility between agroecological practices and irrigation. Yet, this co-existence is not straightforward as the current paradigm is a tendency to make an antagonism between agroecology and irrigated agriculture (pollution, water wastage, soil salinization, biodiversity modification...). Indeed, as shown in Chapter 1, from the point of view of irrigation science, improved efficiencies can be sought through better irrigation scheduling and technological innovation. In the studied case, this pathway can be limited by its effects on increased labor work. In opposition, agroecologist, emphasis agronomic improvements based ecological intensification trough recycling, substitution, diversity, etc. Thus, adopting other technical operations (based on these elements) and even adapting the cropping systems constitutes another option to better valorize the resources. In this thesis, we have shown that although these two methods of improvement of agricultural systems primarily appear antagonist, they can be complementary. We demonstrate the facilitation relation existing between the drip irrigation technology and the adoption of agroecology-compatible practices in the Merguellil downstream plain. This constitutes a significant step forward in research on agroecology in irrigated systems.

From an agronomic point of view, water management is very marginal in research on agroecology and is often limited to the sole improvement of the efficiency of its use. The thesis treats water in irrigated systems from a different angle and shows how access to this resource, where it is a limiting factor, can catalyze the emergence of some agroecology-compatible practices. This analysis is conducted at the plot (sometimes to farm) and TMR levels, and does not imply sustainability at higher organization levels. It also invites to consider these new technologies as potential vectors of new practices, which can be more sustainable despite the threat of a rebound effect at a higher level.

Returning to the ESR conceptual framework presented in figure 1.5, the thesis brings a core set of knowledges concerning the first stage (Efficiency increase)

and to some extend the second stage (substitution) in the Merguellil downstream plain context. It emphasizes the already high efficiency increase potential of these irrigated systems, demonstrated by the estimated excessive amount of water and nutrient used and modelled yield gain potentials. Higher productivity and efficiencies of resources use can be achieved on almost all fields, through optimized irrigation scheduling, or the use for example of manure tea and agroforestry. Concerning substitution, we have shown that there are sets of single practices, related to agroecology, that can be alternatives to conventional practices, that can serve to reduce resources' overuse and wastage, reduce dependency to external input, while increasing productivity. Some are, in this Mediterranean context, specific to irrigated systems, such as organic fertigation or the possibility of integrating trees in the crop system. However, we also show that these innovations are drowned within a wide range of other management rules. The findings are valid for most vegetable crops, since farmers tend to have the same logics of management of vegetable crops as observed during the study.

Furthermore, the findings enable us to support Benouniche et al. (2014)'s statement, that considers drip irrigation performances as a myth. The massive drainage and nitrate leaching revealed in our case-study site, confirmed elsewhere (Laib et al., 2018), show that it is not enough to simply adopt the drip irrigation technology, but more importantly, strategies of fertigation must be upgraded and adapted to the technology. Hence, the results question the position of some authors such as Wezel (2017), presenting drip irrigation as an agroecological practice of water saving to reach efficiencies sought by agroecology. Rather, our results suggest that drip irrigation might be considered as the vector of some environmental-friendly practices, and if managed in the right way, it offers the potential to increase water and nutrient use efficiencies and crop productivity.

6.1.3 Methodological contribution

On the methodological plan, the thesis deals with one of the main challenges of research in irrigation water management: the multidisciplinarity. As mentioned in Chapter 1, each discipline spanned by the subject of irrigation has, so far, the tendency to focus on its own specialty using specific tools (Hsiao et al., 2007). The core findings of this thesis have been obtained using a set of complementary analysis frameworks and tools coming from different disciplines, from typology (agronomy of practices) to qualitative assessment of environmental impacts (hydrology, ecology), and field monitoring and modelling (agronomy, agro-hydrology). Such an approach has not been implemented before, especially concerning questions related to agroecology in irrigated systems. A similar combination of approaches has been implemented to analyze agroforestry systems

in rainfed conditions in Morocco (Temani et al., 2021). In addition, we designed and used methods to implement all these frameworks in highly constraining field conditions, focusing on farmers' practices. Such an environment is particularly unfavorable to in-depth analyses and approaches, as those implemented here.

Beyond the complementarity of analysis frameworks, the originality of the thesis also lies in the use of different but complementary methods of data collection and analysis, from surveys to field measurements and observation or simulation. The diagnostic analysis primarily realized through a typology analysis was undertaken in order to stay in line with one the fundamental principles of agroecology suggesting an understanding of local farming practices and conditions before proposing adaptation solutions. The choice to start by a typology analysis (Figure 6.1) was also dictated by the lack of documentation on TMRs in the Merguellil downstream basin since the widespread adoption of drip irrigation. The typology represents the basis of the study, and made it possible, although only partly, to meet several objectives of the Ph.D. Thus, in this step, we i) thoroughly described the diversity of TMRs, ii) assessed them, iii) identified some agroecology-compatible practices and iv) suggested some alternative management rules exclusively based on local practices. Beyond the necessity to understand how farmers operate, to propose adapted solutions, field monitoring was preferred to controlled experimentation for several reasons:

- the representation of peasant practices in controlled environments is often biased,
- only well-studied and documented practices can be replicated in a controlled environment,
- involving farmers in the experimentation increases the chances that the alternative solution we propose will be suitable for them,

This choice has allowed us to identify the perverse effects of drip irrigation – reflected by a weak appropriation of fertigation management – hitherto hidden by the theoretical performance of this technology. Further, we used a modelling approach based on these field data collected in real environment, which was a real challenge. The use of a modelling approach to represent farmers' fertigation strategies had a twofold advantage. On the one hand, it combined, within a single conceptual framework, very disparate information (agricultural practices, abiotic constraints) to understand plant's responses. On the other hand, it allowed to estimate variables (drainage, nitrate leaching) without going through costly and time-consuming measurements, and to explore the potential effect of an upgrade of farmers' practices without additional experimentation. Despite

numerous sources of uncertainty related to data, modelling gave coherent explanations of the impacts of farmers' TMRs on the studied systems' externalities (yield, drainage, nitrate leaching). The analysis of optimization scenarios, although exploratory, is a way to support our analyses with numerical data. This exploratory analysis, based on simplistic but realistic hypotheses, enabled to confirm the interest of looking at an access to water resources and technology rather as an opportunity than as an obstacle for the transition to more economically and environmentally viable agricultural systems.

6.2 Limits of the study

6.2.1 The scale of analysis and studied systems

In hindsight, this thesis was mainly focused on the efficiency increase stage of the incremental phase of ESR framework. This stage mainly concerns field and farm scales. We have shown that there is a high potential to increase efficiencies of resource use. The levels 2 (substitution) and 3 (Redesign) of the ESR conceptual framework should be studied more thoroughly. Indeed, although we analyzed the interest of the substitution of fertilizers with manure tea and the redesign of the systems into agroforestry systems, the assumptions we made were simplistic and conclusions are exploratory. The strong and widespread adoption of these practices within the plain shows an evident, potentially economic interest of farmers in them. One of the main goals sought by farmers, as shown by Ameur et al. (2020), is economic profitability. Conclusions that emerged from our economic analysis must be taken with caution. Indeed, price volatility can actually make less productive systems more economically viable as price may vary by a factor of two. We suggest that the economic interest and ecosystem services provided by the alternative practices have to be more assessed in further studies. Furthermore, as suggested by Duru et al. (2015) and Rundgren (2015), the evolution of irrigated systems can get stuck in unsustainable states if the changes implemented are solely incremental ("Efficiency increase" or "Substitution"). Our works are complementary with Ameur et al. (2020)'s studies and both represent springboard towards redesign practices, based on local knowledge. However, a limit of the thesis was the lack of detailed field data to support the analysis of agroecological scenarios. However, important efforts have been made to monitor agroforestry system. The experimentation was not as satisfactory as expected. As possible perspectives of research at plot level, the agroecology-compatible practices described in this study should be further studies, seeking what logics affect the adoption of these practices. What biophysical processes are affected at plant scale? At territorial scale, one needs to perform assessment of the level of adaptation of the agroecology-compatible

practices. Based on these practices, co-design of alternative systems could be realized leading to substitution and redesign phase.

6.2.2 A farmer and field-focused analysis

Our methodological approach, although centered on the farmer, was not implemented in a participatory way. Thus, the contributions of this thesis (typical TMRs, alternative practices such as optimized irrigation scheduling, etc.) would require a validation involving farmers and local stakeholders. In agreement with Levard et al. (2019), this consultation on the results and the potential effects of the adoption of alternative practices is essential. To overcome the weakness of the thesis, a restitution / validation workshop, gathering the concerned stakeholders could have been organized [1]. This would be an opportunity to discuss whether new cropping systems can be designed from the proposed TMRs. It could also allow to verify in what extent farmers might be willing to adopt the alternative practices suggested by the thesis. For instance, we are aware that our optimized irrigation scheduling can be too binding for farmers, as these recommend more frequent irrigation and "shorter" irrigation. Some trade-off frequency-dose (duration) could be co-elaborated in a participative approach. Pushing further, a participatory implementation of our methodology is also possible. For instance, one could realize farmer and expert-based typology and assessment of TMRs. Such an approach would have the advantage to allow a co-description/evaluation of the existing management rules and a co-conception of alternative solution. Indeed, the development of an agriculture enhancing ecosystem services, involves co-evolution of technological, social, economic and even institutional dimensions, and lies on appropriate interactions between stake-holders of the farming system, the supply chain and natural resources management at local scale (Duru et al., 2015). These interactions are not explicitly taken into account in the thesis. Audouin et al. (2019) support the importance of the co-evaluation and the necessity to have a multi-stakeholder representation in the approaches. Some results coming from a participatory implementation of our methodology might probably differ from ours. Different scenarios might also be chosen. However, at this stage of understanding, knowledge stemming from the numerous interviews with stakeholders – although not explicitly described and analyzed – suggests that the gradient of environmental-friendly practices is also perceived as such by farmers and should emerge from participatory implementation of our methodology.

[1] This step was planned but not implemented, due to Covid-19 pandemic restrictions.

6.2.3 Comparison of systems and criteria used

The monitored plots in 2019 were close to the cluster paragons defined in the typology analysis (chapter 2), hence giving for one crop cycle, data on the resulting yields and water and fertilizer use. This completes the initial, more qualitative analysis concerning these main variables. In the following assessments, fields were compared to each other. This allowed to compare for each efficiency indicator we computed, the fields relatively to the best performing field. No reference situation was thus considered. According to Levard et al. (2019), it is an apparent limit of the study. Indeed, the study should be based on the comparison between field or farms where certain agroecological practices and systems are implemented and "reference" fields or farms where these are not implemented. In fact, it is more complex to identify a reference situation when the study involves existing practices, even the more when a large variety of practices are implemented in a wide variety of production systems. A reference field would be necessary to test newly designed cropping systems or management rules.

Further, the quantitative assessment realized in the thesis, based on the indicators traditionally used, gives it a high degree of generality. The main limitation lies in the dimension and criteria assessed. Indeed, the thesis focused on agro-environmental aspects and especially productivity and the resources use efficiencies. Additional dimension should have been integrated (the effects of greenhouse gas emissions, the effectiveness of pest and disease control, socio-economic performances). More specifically, soil health especially soil biological activity, although initially planned, was not included in the study due to the 2020 lockdown. Soil is a key component of agricultural ecosystems and might not be occlude in agroecological assessment of farming systems. Indicator such as basal respiration may have provided additional interesting insights to the study. We initially planned to compare at least both environmental and non-environmental friendly TMRs regarding basal respiration. Administrative shutdowns did not allow us to realize the laboratory analyses. Hence, further studies might investigate these aspects. For instance, a multicriterial assessment of TMRs could be undertaken, in order to broaden the dimension and scale of analysis. Moreover, a limit of the quantitative assessment was the low number of fields per cluster to compare the results. The fact that only one field represented cluster 3, 4 and 5 for example, did not allow to assess the intra-cluster variability of performances. Further research might investigate this intra-cluster productivity and eventually compare local and hybrid varieties within clusters.

6.2.4 Two-year complementary analyses

Multiple complementary approaches have been used to describe and assess the TMRs. Nonetheless, these approaches were applied on different cropping years

(2018, 2019). To do so, we assumed that farmers' strategies might not change substantially over time. Comparison of some data collected both years revealed there were no significant changes in farmers' strategies (e.g. moving from environmental-friendly to non-environmental friendly).

However, this hypothesis can be called into question as some of the agronomic and environmental performance achieved in 2019 can be (partly) attributed to changes that occurred between these two periods, particularly in relation to factors such as climate, economic conditions and different social conditions. As illustration, some farmers said during the surveys in 2019:

- "*I am often out of the farm this year. I am supplying less fertilizers*" (P3)
- "*I am not expecting a high yield this year due to weed attacks, I am not going to invest in this field anymore*" (P7)
- Another farmer decided not to apply organic manure in 2019; we suspected economic constraints

Thus, it would be interesting to implement the approaches in both 2018 and 2019 cropping years. However, proceeding that way would have generated additional methodological questions: which fields to monitor at the beginning of the study? how to justify the choice of these fields? Which data to collect? How to collect these data? As shown in figure. . . , we intentionally realized the typology and qualitative assessment in 2018, then the quantitative assessment the following year as further actions, based on the Bos et al.' (2004) conceptual framework.

6.3 Perspectives

6.3.1 Agroecological perspectives in the Southern Mediterranean irrigated systems

Several authors have described the trajectory of the irrigated agriculture in the Southern Mediterranean region. Massuel et al. (2017) showed the high amounts of water withdrawn at farm level each year in the Saiss plain in Morocco, the Merguellil downstream plain in Tunisia and the Ziban in Algeria. Venot et al. (2017) associated these withdrawals to a rebound effect of the adaption of the drip irrigation technology. Pradeleix et al. (2018) for their part, highlighted energy used for groundwater pumping as one of the main processes contributing to the environmental impacts of farming practices on natural resources a territorial scale in the Merguellil downstream plain. Our study does support these overviews and shows the importance of the withdrawals, their impacts at plot scale and the necessity to improve the efficiencies. According to Pradeleix et

al. (2018), fertilization is the most important factor contributing to environmental impacts of farming practices. These findings confirm our results and are supported by other studies (Laib et al., 2018). Furthermore, this thesis support the idea that innovations cannot solely achieve the purpose of sustainable development in the agriculture sector in the Maghreb countries (Khaled, 2017). There is still a long way to go to achieve the transformative phases of the agroecological transition of the production systems in Tunisia as shown in this thesis, in Morroco (Chbika and Aouane, 2021) and in the Maghreb countries in general. Agroecology-compatible practices and more generally environmental-friendly management which are remnants of ancient less-performing systems are doomed to gradually disappear in these regions. Indeed, considering the dynamics of changes in the production systems described by Azizi (2018) in the Merguellil downstream plain context, farmers tend to move towards more high value-added crops (market gardening and orchards) and land intensification with more productive TMRs. In such global intensification context, environmental-friendly TMRs will inevitably become less present. Hence, actions in the short and medium terms should involve the Efficiency increase and Substitution phases of the in agroecological transition process in the Southern Mediterranean irrigated systems and sought to preserve the environmental-friendly TMRs.

6.3.2 Towards a territorial evaluation of irrigated market gardening crops

The approach implemented in this thesis is adaptable and applicable to other crops and other territories in order to assess the conditions of a transition towards more sustainable systems. The study can contribute to a broader field of research on regional sustainability of cropping practices. Indeed, the methodology implemented in chapter 1 defined the key TOs related to TMRs. However, the regional representativity of these TMRs must be studied. It could be more easily obtained by carrying out surveys on the key variables. This would allow to identify new specificities of productions, changes in the link farm-TMR types, management rules and new innovative practices, to be taken into account for the design of agricultural policies. On another hand, the method could also be applied to other emblematic crops to test the consistency of our conclusions. It would be interesting, for example, to apply the approach to the case tomato or watermelon-based systems in the Merguellil plain, or in other country of the Southern Mediterranean, the onion-based systems of the Saiss plain in Morocco. As suggested by Duru et al. (2015) and Rundgren (2015), the evolution of irrigated systems can get stuck in unsustainable states if the changes implemented are solely incremental ("Efficiency increase" or "Substitution"). Our works are

complementary with Ameur et al. (2020)'s studies and both represent springboard towards redesign practices, based on local knowledge. However, a limit of the thesis was the lack of detailed field data to support the analysis of agroecological scenarios. Although important efforts have been made to monitor agroforestry system, the experimentation was not as satisfactory as expected. As possible perspectives of research at plot scale, the agroecology-compatible practices described in this study should be further studied. What are the real cost related to these? What biophysical processes are affected at plant scale? Then, at territorial scale, one needs to perform assessment of the level of adaptation of the agroecology-compatible practices. Based on these practices, co-design of alternative systems could realized leading to substitution and redesign phase.

6.3.3 Socio-economic factors influencing management logics

To broaden the thoughts, a more global analysis could to be carried out at the farm and even territorial scales. In chapter 2, we identified the key structural variables allowing to identify which farm implemented each type of TMR. Beyond the structural data, which logics drive the operational choices of farmers? We hypothesized that strong social, economic and environmental constraints in irrigated areas (Jamin et al., 2011) might enable a diversity of farming practices, and showed that environmental-friendly systems arose from this local diversity. We also showed that facilitated access to water resource and drip irrigation are not systemically an obstacle for the adoption of more environmental-friendly farming practices. In what extent social, economic and environmental constraints contribute to this adoption? What are the farmers' decision rules in front of these constraints? Further, as major contribution, the thesis reassesses the place given to water and irrigation in agroecology. Would the assertion that agroecology and irrigation are compatible be valid in any irrigated system?

6.4 General conclusion

Irrigated agriculture meets numerous challenges worldwide and more specifically in the southern Mediterranean where irrigation is instrumental for a viable agriculture, but where water is often managed in an unsustainable way. Although the principles of agroecology and those of irrigated agriculture are often considered to be contradictory, agroecology can actually be perceived as an alternative solution to deal with the challenges of irrigated systems based on drip irrigation technology. This thesis analyzed this technology as a potential vector of interesting practices to initiate a transition towards more sustainable systems. The general problematic of the study was: how can the multidimensional concept of agroecology be integrated into the understanding of irrigated

systems using drip irrigation? Is the implementation of agroecological practices in these systems a solution to resource use efficiency and environmental issues? Answers are brought to these questions by analyzing access to water and the use of drip irrigation in a broader perspective using different approaches. Thus, the thesis reassesses the paradigm tending to make an antagonism between agroecological principles and irrigation by showing possibilities of coexistence of agroecological practices and irrigation within the Merguellil downstream plain, a relatively small territory where farmers are confronted the same constraints. This was done by identifying sets environmental-friendly technical management rules (TMRs) within a large diversity of TMRs. TMRs were accessed in both qualitative and quantitative manners. The findings showed that, although farmers did not design their TMRs in an agroecological perspective, they usually combine single agroecological practices to less virtuous practices to design more or less productive systems. Some TMRs adaptable to different cropping systems allow farmers to reach high productivities and efficiencies. Scientifically, this PhD uses approaches and tools from several disciplines including agronomy, hydrology and more specifically irrigation sciences. A set of statistical tools were combined to perform the typology analysis. Opitirrig, a model combining a crop model and water and nitrogen balances model was used to represent, in a unique conceptual framework, the farmers' strategies and the pedoclimatic conditions. The use of this model enabled to project the possible resource savings and yield gain related to an eventual optimization of the farmers' irrigation strategies. An integrative analysis of optimization strategies of the cropping systems was performed by applying both the generated optimization of irrigation scheduling and the integration of two representative agroecological practices observed in the region. These widespread practices might enable farmers to achieve economic goals or higher agro-environmental performances. This study raises further questions concerning the agroecological transition of irrigated systems. In a next step, a global analysis at the farm scale could be realized to understand how TMRs are arranged within cropping systems.

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Appendix A

Experimental conditions

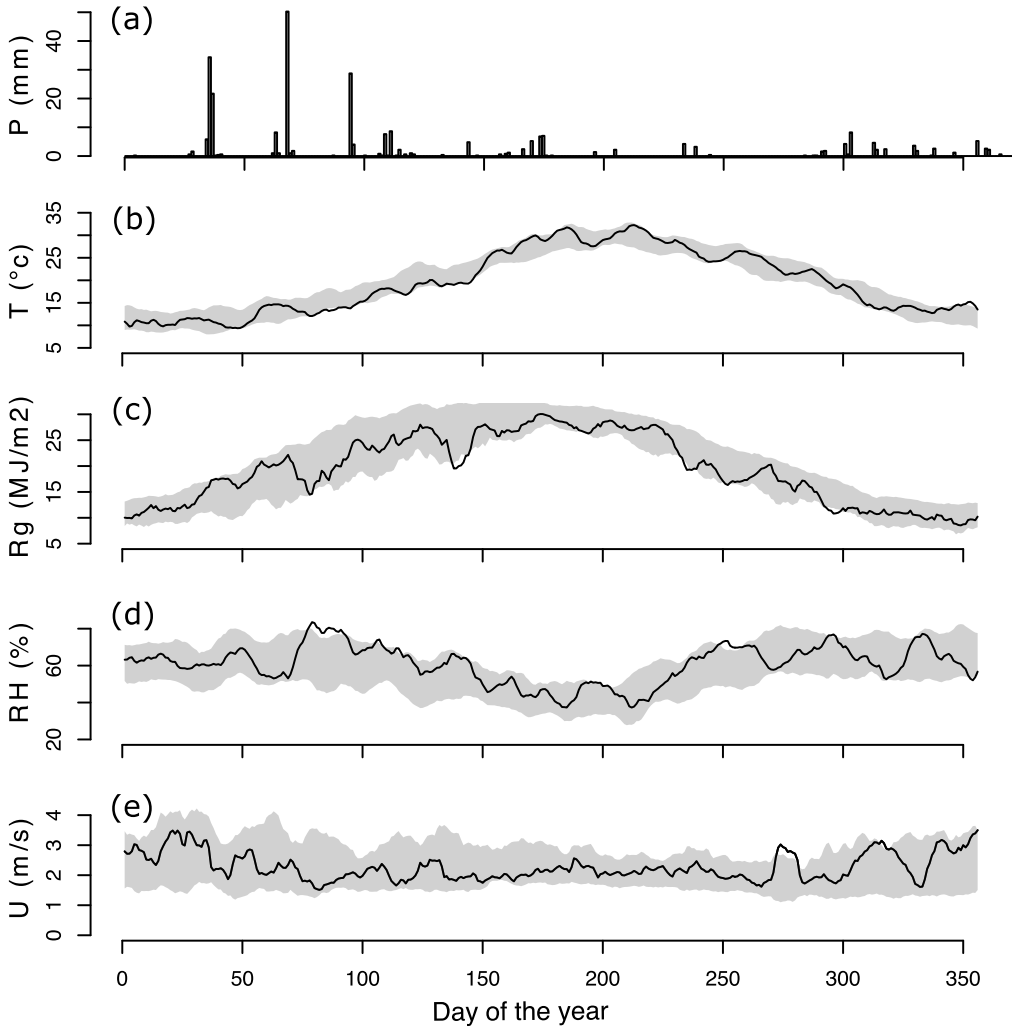


Figure A.1: Meteorological data measured at a local weather station (a) rainfall (b) average daily temperature; (c) solar radiation; (d) air relative humidity; (e) average wind speed. The line represent data measured in 2019. The grey band represents the 10 years daily average

Appendix B

Additional figure of statistical analyses (Chapter 2)

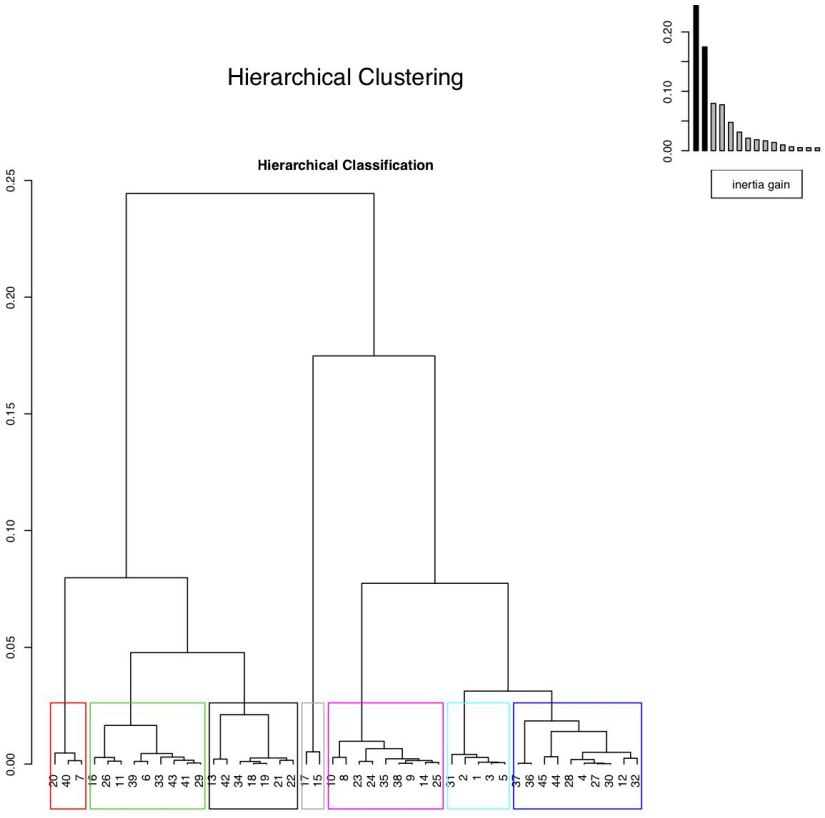


Figure B.1: Cluster tree obtained after HAC

Appendix C

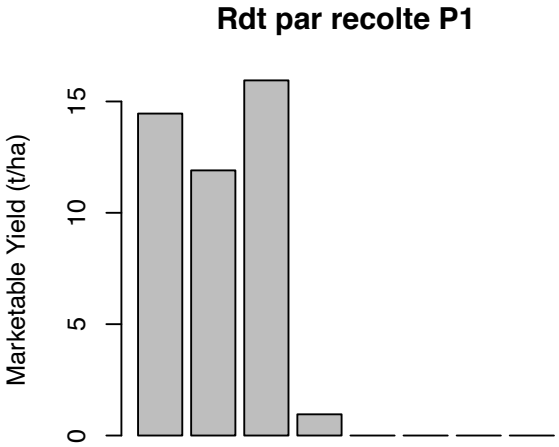
Scenarios and related agro-environmental variable and socioeconomic variables (Chapter 5)

Cluster	Plot	Scenario	Water Input	Drainage	N Input	N Leaching	Yield	Ratio	Water Energy cost	Labor cost	Workload	Gross revenue
			mm	mm	kg/ha	kg/ha	T/ha		-	-	-	TND
Cluster 1	P1	S1	2800	2380	152	203	44	0	n/a	n/a	n/a	44000
		S2	480	0	152	0	70	0.59	---	+++	+++	70000
		S3	2800	1780	152	158	35.2	-0.2	NE	+++	NE	41700
		S4	1080	0	152	0	56	0.27	---	+++	+++	62500
	P6	S1	565	368	183	213	29	0	n/a	n/a	n/a	29000
		S2	240	0	183	0	32	0.1	---	NE	NE	32000
		S3	565	0	183	0	29	0	NE	+++	NE	35500
		S4	840	0	183	0	32	0.1	NE	+++	NE	38500
Cluster 2	P3	S1	1870	1475	126	126	66	0	n/a	n/a	n/a	66000
		S2	509	0	126	0	75	0.14	---	+++	+++	75000
		S3	1870	875	126	81	66	0	NE	+++	NE	72500
		S4	1109	0	126	0	75	0.14	---	+++	+++	81500
	P10	S1	1550	1350	165	218	12.6	0	n/a	n/a	n/a	12600
		S2	231	0	165	0	32	1.54	---	+++	+++	32000
		S3	1550	750	165	173	15.12	0.2	NE	NE	+++	21620
		S4	831	0	165	0	38.4	2.05	---	+++	+++	44900
	P11	S1	335	165	97	130	35.7	0	n/a	n/a	n/a	35700
		S2	250	0	97	0	35.7	0	NE	NE	NE	35700
		S3	335	0	97	0	35.7	0	NE	NE	NE	42200
		S4	850	0	97	0	35.7	0	+++	NE	NE	42200
Cluster 3	P4	S1	756	293	113	111	33	0	n/a	n/a	n/a	33000
		S2	536	0	113	0	79	1.39	---	+++	+++	79000
		S3	756	0	113	0	39.6	0.2	NE	+++	+++	46100
		S4	1136	0	113	0	94.8	1.87	+++	+++	+++	101300
Cluster 4	P8	S1	1080	894	191	229	10.7	0	n/a	n/a	n/a	10700
		S2	570	0	191	0	23	1.15	---	+++	+++	23000
		S3	1080	294	191	184	10.7	0	NE	+++	+++	17200
		S4	1170	0	191	0	23	1.15	NE	+++	+++	29500
Cluster 5	P2	S1	1744	1200	72	123	55	0	n/a	n/a	n/a	55000
		S2	585	0	72	0	82.22	0.49	---	+++	+++	82220
		S3	1744	600	72	78	44	-0.2	NE	NE	---	50500
		S4	1185	0	72	0	65.776	0.2	---	+++	+++	72276
Cluster 6	P5	S1	700	420	100	140	8	0	n/a	n/a	n/a	8000
		S2	580	0	100	0	23.75	1.97	NE	+++	+++	23750
		S3	700	0	100	100	6.4	-0.2	NE	+++	NE	12900
		S4	1180	0	100	0	19	1.38	+++	+++	+++	25500
	P7	S1	373	186	52.5	93	3.16	0	n/a	n/a	n/a	3160
		S2	600	0	52.5	0	22.5	6.12	+++	+++	+++	22500
		S3	373	0	52.5	0	3.16	0	NE	+++	+++	9660
		S4	1200	0	52.5	0	22.5	6.12	+++	+++	+++	29000
	P9	S1	262	156	91	99	5.2	0	n/a	n/a	n/a	5200
		S2	616	0	91	0	25.2	3.85	+++	+++	+++	25200
		S3	262	0	91	0	5.2	0	NE	+++	+++	11700
		S4	1216	0	91	0	25.2	3.85	+++	+++	+++	31700

Figure C.1: Scenarios and related agro-environmental variable and socioeconomic variables

Appendix D

Marketable yield per plot and harvest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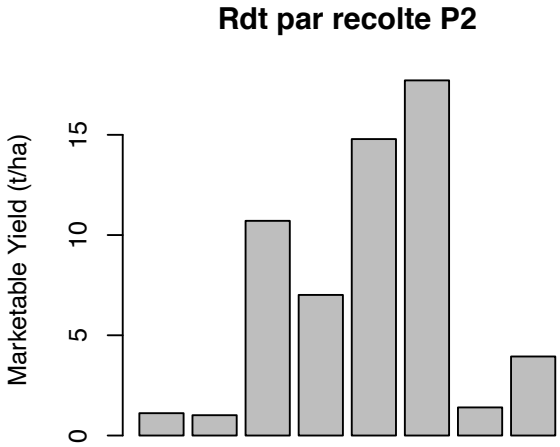
Marketable Yield (t/ha)
0
5
10
15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Marketable Yield (t/ha)
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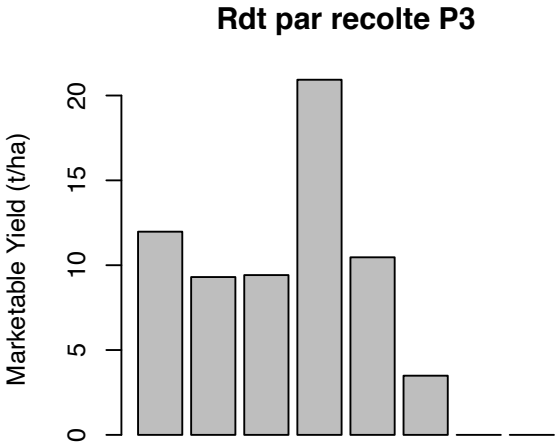
5
10
15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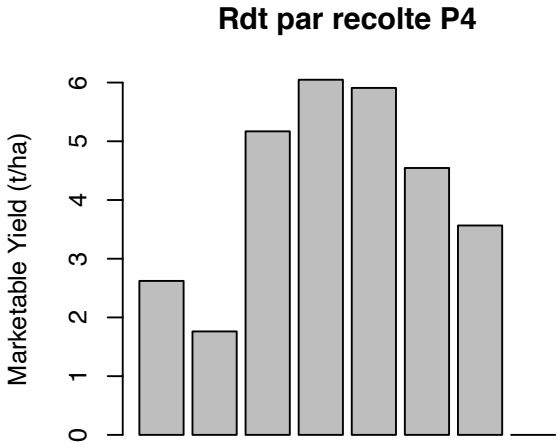
Marketable Yield (t/ha)
0
5
10
15
20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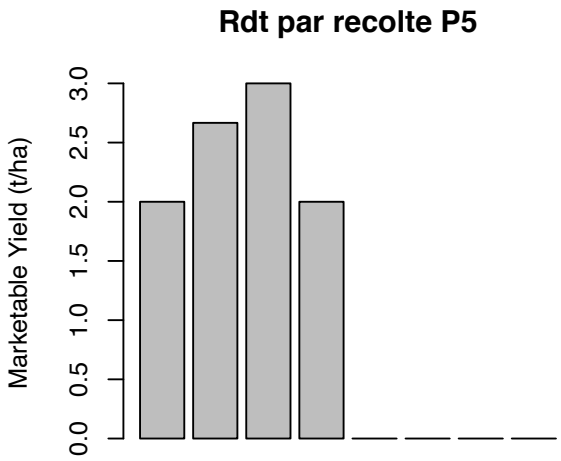
Marketable Yield (t/ha)
0
1
2
3
4
5
6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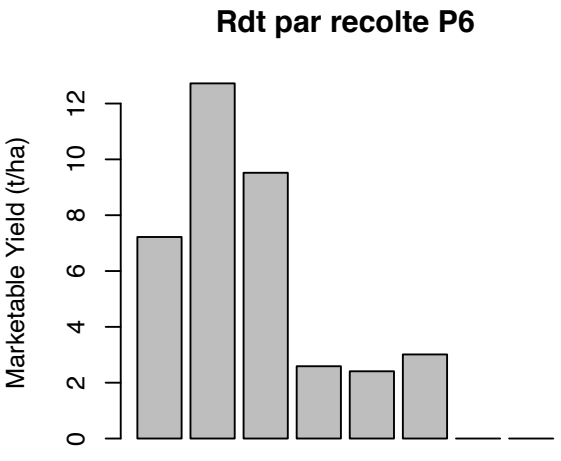
Marketable Yield (t/ha)
0.0
0.5
1.0
1.5
2.0
2.5
3.0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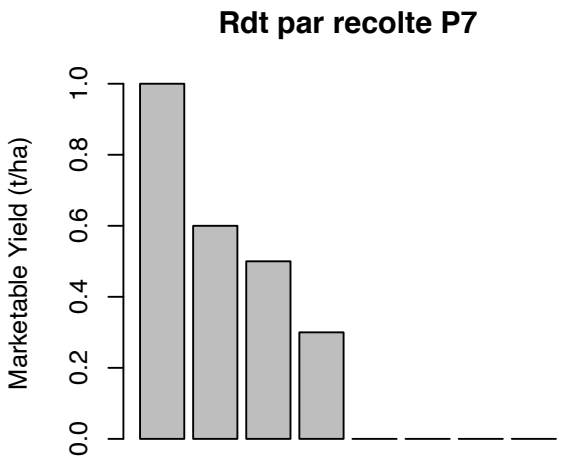
Marketable Yield (t/ha)
0
2
4
6
8
10
12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Marketable Yield (t/ha)
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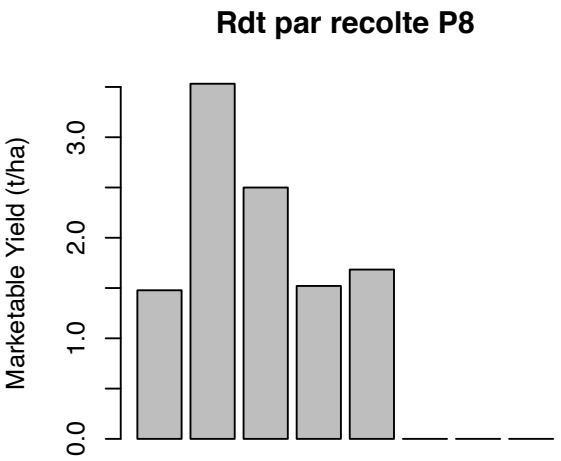
0.2
0.4
0.6
0.8
1.0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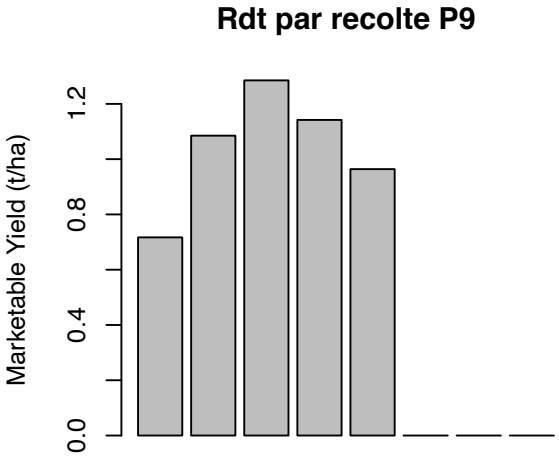
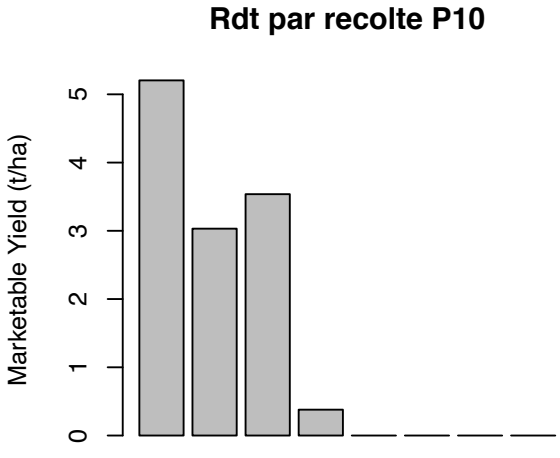
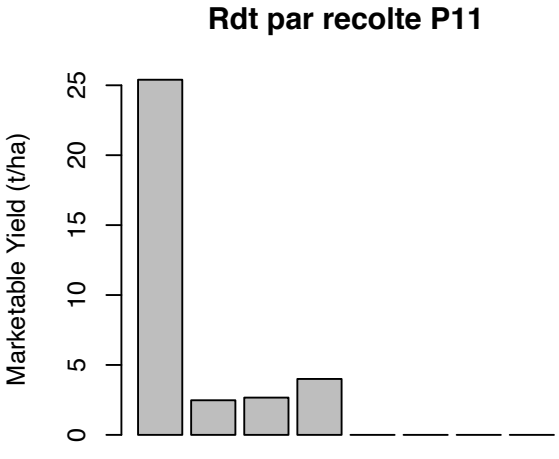
Marketable Yield (t/ha)
0.0
1.0
2.0
3.0







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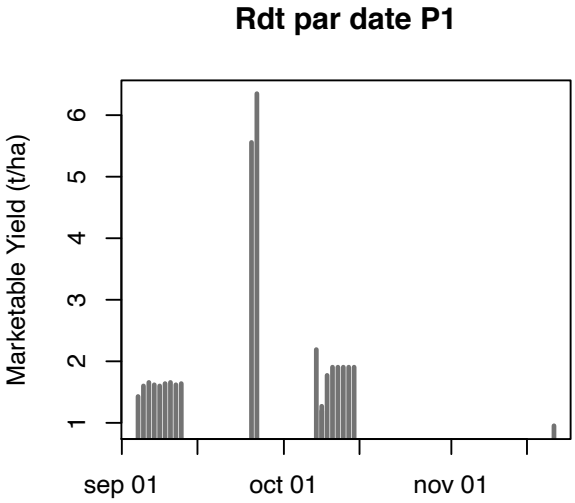
Hybrid = P1, P2, P3,P4, P6, P10, P11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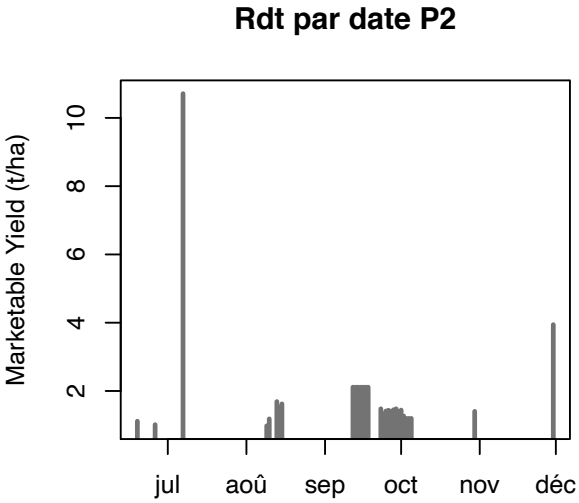
Marketable Yield (t/ha)
1
2
3
4
5
6
sep 01
oct 01
nov 01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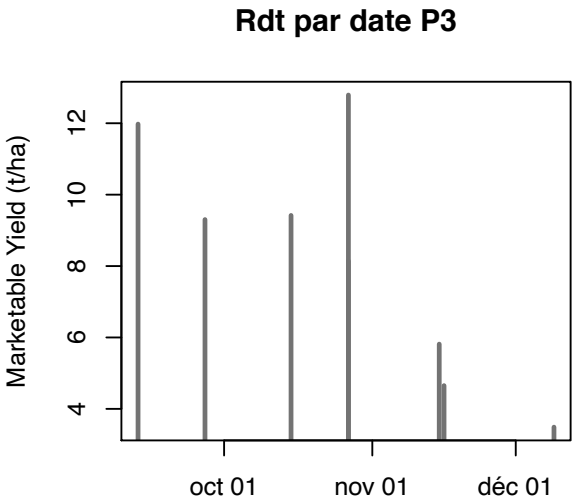
Marketable Yield (t/ha)
2
4
6
8
10
jul
aoû
sep
oct
nov
déc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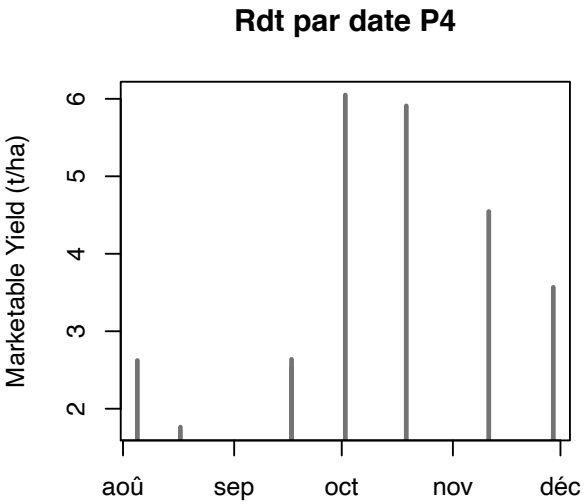
Marketable Yield (t/ha)
4
6
8
10
12
oct 01
nov 01
déc 01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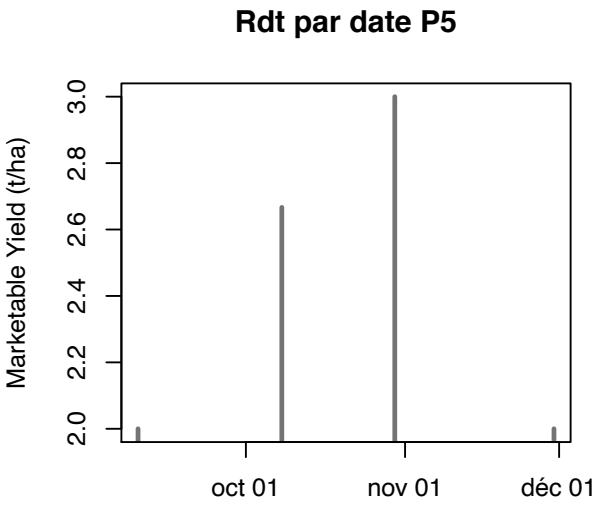
Marketable Yield (t/ha)
2
3
4
5
6
aoû
sep
oct
nov
déc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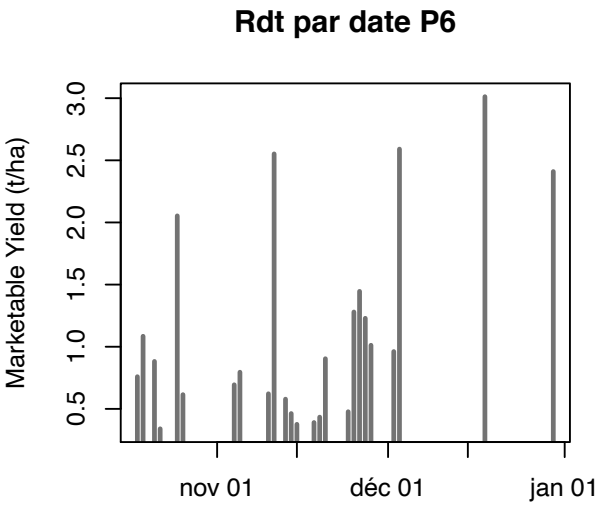
2.0
2.2
2.4
2.6
2.8
3.0
oct 01
nov 01
déc 01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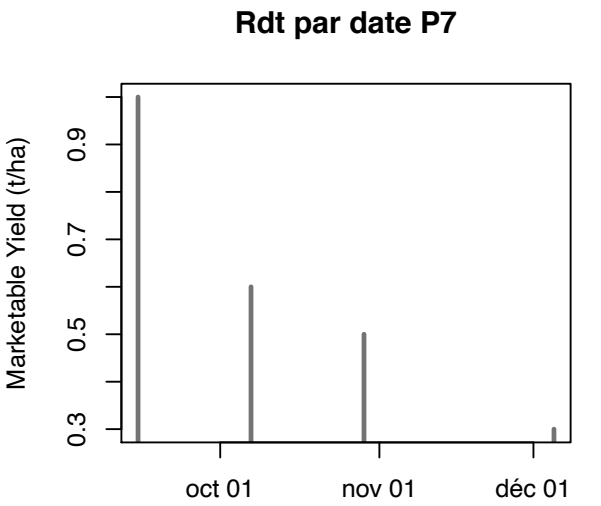
1.0
1.5
2.0
2.5
3.0
nov 01
déc 01
jan 01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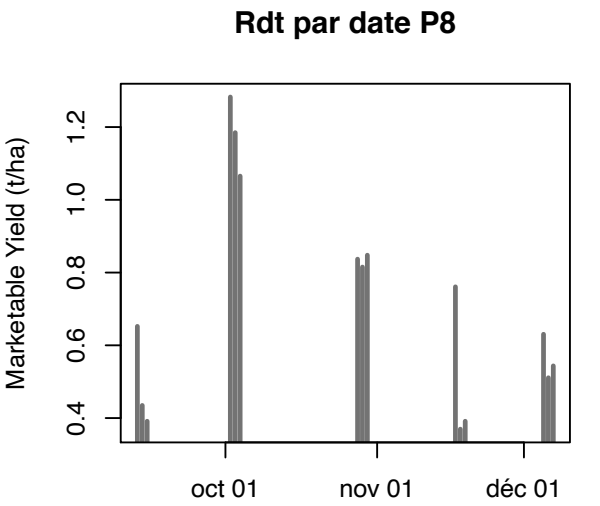
Marketable Yield (t/ha)
0.3
0.5
0.7
0.9
oct 01
nov 01
déc 01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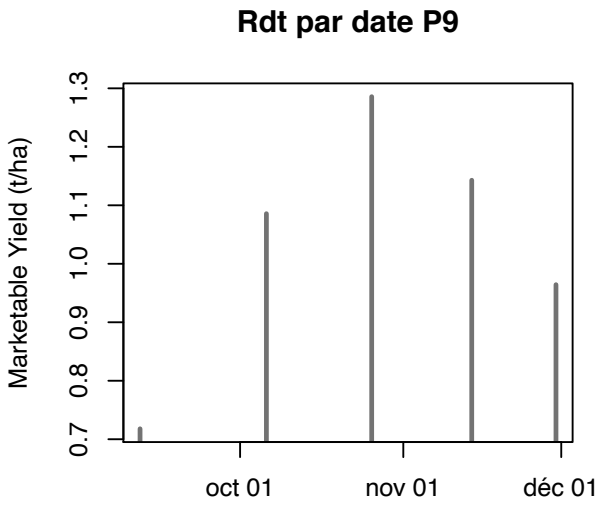
Marketable Yield (t/ha)
0.4
0.6
0.8
1.0
1.2
oct 01
nov 01
déc 01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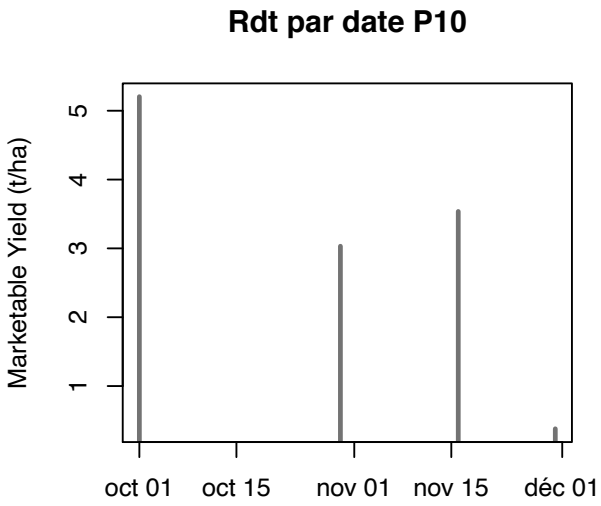
0.8
0.9
1.0
1.1
1.2
1.3
oct 01
nov 01
déc 01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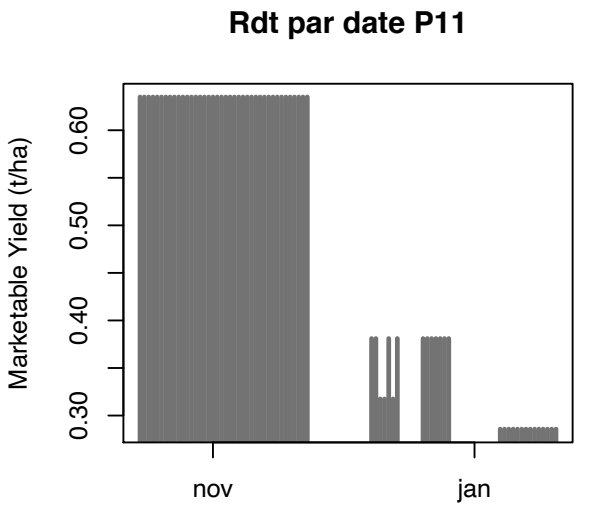
Marketable Yield (t/ha)
1
2
3
4
5
oct 01
oct 15
nov 01
nov 15
déc 01


Rdt par date P11
Marketable Yield (t/ha)
0.30
0.40
0.50
0.60
nov
jan

Appendix E

Conference abstracts

1. In the search for innovative agroecological farming practices in irrigated landscapes of North Africa: Case of Kairouan plain in Central Tunisia. PS-7.3-03. Akakpo Koladé, Leauthaud Crystèle, Ben Aissa Nadhira, Bouarfa Sami, Bahri Akiça. 2018. In : Book of abstracts of the XV European Society for Agronomy Congress : "Innovative cropping and farming systems for high quality food production systems". Agroscope. Genève : Agroscope, Résumé, 80. European Society for Agronomy Congress (ESA 2018). 15, Genève, Suisse, 27 Août 2018/31 Août 2018. http://www.esa-congress-2018.ch/wp-content/uploads/2018/08/ESA2018_AbstractBook_A4-1.pdf

PS-7.3-03

In the Search for Innovative Agroecological Farming Practices in Irrigated Landscapes of North Africa: Case of Kairouan Plain in Central Tunisia

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Abstract: Irrigated agriculture is instrumental for the economy and employment in North Africa countries. However, farmers in the Maghreb region face, on the one hand, multiple environmental and climatic risks, and on the other, economic constraints that, combined together, can lead to the vulnerability of these rural populations. Assuming that strong capacities of adaptation and innovation potentials exist within small-scale irrigated farming systems, this study aimed to identify and characterize existing eco-efficient and resilient farming practices in the Kairouan irrigated plain in Central Tunisia. The latter is entirely cultivated, with a wide variety of crop types such as market gardening, arboriculture and cereals. Representative of small-scale family farming systems in the irrigated plains of Tunisia, this study site lends well to work on the characterization of agroecological practices in a semi-arid irrigated environment. Semi-structured interviews were conducted with farmers, first, to identify low-input practices at the plot and farm scale, second, to apprehend the determinants and the objectives of these practices. The sampling procedure sought to explore the wide range of existing practices, and was thus partly based on the farmers and the local agricultural administration knowledge and networks. The study shows that farmers usually combined different cropping systems, mostly for economic reasons (improved water and land use, increased monetary income by reducing chemical inputs). Low chemical-input or water-use practices, related to agroecology, were observed, especially for watermelon and pepper, which are commonly associated with leguminous species. Agroforestry practices, associating different tree species (mainly olive trees) to other crops, or intercropping (market gardening, cereals), were also common. Some farmers integrated animals in "a no lost integrated farming system". Furthermore, a little-known, but very innovative practice observed, was irrigation using water coming from organic fermentation, leading to a significant reduction in the need of chemical inputs. All these practices, which are particularly present in small rural farmers, who represent the great majority of the farmers in Tunisia and in Maghreb, show the existence of knowledge on which an agroecological transition could be initiated. Identifying such local agroecological practices is a first step in their adoption and promotion, as decision makers increasingly seek to take into account the environmental impacts of agriculture in the Maghreb.

Keywords: Agroecological practices, agroecology, farming system, irrigated plains, Kairouan, Maghreb, transition.

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Metagenomics of Asparagus Field Soils Treated with Biostimulants

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Abstract: Metagenomic studies of soils allow to reveal different microbiota compositions in various organic or conventional agricultural systems. The present study combined biostimulants trials and metagenomics, with the expectation that a potential yield increase could be linked to a microbiota variation. The tests were carried out in a perennial cropping system of asparagus, on a sandy and silty soil, which has been treated with 2 commercial biostimulants, Exuroot (T1) and Exuroot added with Cérès (*Pseudomonas fluorescens* and *Trichoderma harzianum*) (T2). Biostimulant treatments were applied 4 times between mid-July and mid-September 2016, on experimental units (EU) of 800 m^2 (3 repetitions) Asparagus shoots were harvested from March to April 2017, counted every two days in each EU and ranged in 4 group size groups. Results were then grouped into two time spans; corresponding to the 4 first collections and the 4 following collections. ANOVA and TUKEY KRAMER tests were applied to infer statistical differences. The total numbers of collected shoots per experimental unit were 182, 185 and 199 shoots, for the control, T1 and T2 respectively, equivalent to 2279, 2317 and 2492 shoots per ha, respectively, representing an increase of 9.34 % in T2 when compared to the control. The main contribution to this increase was due to lower size shoots, considered as second quality products. For the metagenomics analysis, for each of the 3 modalities and their repetitions, 50 g of rhizosphere soil were sampled from 10 points at depths between 20 and 40 cm and the control modality was sampled at the beginning and at the end of the experiment. Pooled sampling points were homogenized and DNA was extracted from 10 g subsamples. Whole metagenome shotgun sequencing was carried out with an Illumina MiniSeq using 2x150-bp paired-end reads. Sequencing yielded between 3,360,000 reads (0.5 Gb) and 12,350,000 reads (1.85 Gb) per sample. Bioinformatic analysis and identification of operational taxonomic units (OTUs) were performed using One Codex. A wide diversity of OTUs was retrieved from these soil samples, in which the classes Alphaproteobacteria and Actinobacteria were dominant. The 10 most abundant genera, representing between 29.43% and 42.8% of all species in all samples, were *Bradyrhizobium*, *Mesorhizobium*, *Microbacterium*, *Mycobacterium*, *Nocardioides*, *Pseudomonas*, *Rhizobiumm*, *Sphingomonas* and *Streptomyces*. Most of these genera showed important diversity, with dozens of different OTUs in each sample. Differences between microbiota of the three modalities were little and analysis should be refined to explain the yield increase of T2 modality.

Keywords: soil metagenomics; biostimulants: asparagus culture; *Pseudomonas fluorescens*; *Trichoderma harzianum*

2. Agroecology in a semi-arid Mediterranean area: from real practices to integrated agroecological systems? Akakpo Koladé, Ameur Fatah, Bouarfa Sami, Leauthaud Crystèle. 2019. European Association of Agroecology. Heraklion : European Association of Agroecology, Résumé, 1 p. Agroecology Europe Forum. 2, Heraklion, Grèce, 26 Septembre 2020/28 Septembre 2020.

Agroecology in a semi-arid Mediterranean area: from real practices to integrated agroecological systems?

The challenge of agriculture in the up-coming decades is to feed an ever-increasing population while reducing or getting rid of chemical inputs and preserving biodiversity and natural resources. In arid and semi-arid areas of the Mediterranean basin, farmers have to face this challenge, alongside multiple environmental and climatic risks. Due to low rainfall, irrigation is instrumental for agriculture and consequently for economy, in these areas. So far, irrigation has been analyzed in terms of eco-efficiency, and is commonly associated with intensification and pollution. First, this study aimed to identify, in a semi-arid irrigated area, a set of farming practices, already implemented by farmers, with agroecological potentials. We present in this communication two "virtuous" farming systems, compared to more conventional and intensive systems. Second, based on the results from 65 semi-structured interviews, a hypothetical plot with a more agroecological management style was designed. The study was carried out in the Merguellil irrigated plain in Central Tunisia, which is entirely cultivated, with a wide variety of crop types such as horticulture, fruit trees and cereals. A first farmer installed at the plot scale, a relay cropping of fava bean (Vicia faba) with pepper (Capsicum annuum) in intercropping with olive trees (Olea europaea). In this agroforestry system, the plot was further surrounded by a windbreak cereal (sorghum) belt. The farmer used old and local varieties, very resistant to pest attacks and that require low chemical inputs, resulting in lower cost of production. Seeds were saved and reused. At the farm level, crop residues (pepper, fava bean, olive tree pruning residue) and cereals were used for livestock feeding. Another farmer used manure as an organic fertilizer after a fermentation process. This practice lead to a substantial reduction of chemical nitrogen fertilizer use. In addition, he applied a water stress period at the beginning of the cycle, in order to "stimulate root growth and improve the plant's absorption capacity". This allowed him to avoid the use of a root growth accelerator. In both cases, different types of spatial crop rotations and successions were set up with frequent fallow periods in order to restore soil fertility. However, these interesting practices coexist with other less virtuous practices. For example, most farmers continued to intensively apply pesticides and used very high quantities of chemical fertilizers. These farmers were mostly specialized in market garden and fruit trees, extremely water consuming. They generally used high yielding varieties, less resistant to pest attacks. Furthermore, the study showed that farmers usually combined agroecological practices for different purposes: i.e. income increase, soil fertility improvement, land-use optimization. All the practices mentioned above could be combined on a single plot/farm, giving a hypothetical system with a more agroecological orientation. With an adapted water and fertilization management, such a system could improve water and fertilizer efficiency and maintain soil quality. But this may not necessarily lead to better pest control or better yields. These practices remain to be evaluated and would be adopted by farmers only if they see it as a clear interest.

3. Irrigation and fertigation practices in small-scale family farming systems for water and nutrient efficiency in semi-arid Mediterranean areas. Akakpo Koladé, Leauthaud Crystèle, Bouarfa Sami. 2019. IRSTEA. Montpellier : IRSTEA, Résumé, 1 p. Water Savings in Irrigation, Montpellier, France, 13 Novembre 2019/14 Novembre 2019. https://watersaving.sciencesconf.org/289940

Irrigation and fertigation practices in small-scale family farming systems for water and nutrient efficiency in semi-arid Mediterranean areas

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Abstract

Efficient use of water and nutrients in irrigation system is important in arid and semi-arid regions, where water is a limiting resource. This study aims to analyze irrigation and fertigation practices for a widespread crop (pepper, *Capsicum annuum*) in Tunisia, in a context of highly diverse agricultural practices. The study took place in the irrigated plain of the Merguellil river in Central Tunisia, characterized by its high diversity of crops and practices. In 2019, irrigation and fertilization practices involved in pepper crop cultivation watered by drip irrigation, were compared on fourteen plots. This was carried out through an approach coupling semi-directive surveys with farmers and monitoring of irrigation, done using a temperature logger installed on the irrigation pipes and allowing the detection of irrigation duration. The study covered the three main seasons of pepper cultivation (Spring, Summer and late Summer). The results showed globally an opposition of two main logics. On the one hand, there are strategies aiming to a significant water supply during the first days after planting, followed by a non-irrigated period, forcing the plant to "tap into the soil water reserves", then irrigation at regular rates (once every three to five days or more) thereafter, sometime alternate with fertigation. On the other hand, there are strategies of regular water and nutrients supply, taking into account crop requirements: low water inputs at the beginning (on daily or once every two to four days rate), followed by a progressive increase. In this strategy, application of fertilizers through the drip irrigation occurred right after the first irrigations, the farmer alternating up to three irrigations for one fertigation. Commonly, fertilization was fractioned and application was done in the last quarter of watering time in order to avoid/reduce nutrient leaching. The number of splits varied significantly from a farmer to another and from a strategy to another. These irrigation and fertigation practices may have different effects on the system outputs, mainly on water and nitrogen efficiency and yield.

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Appendix F

Thesis defense



Figure F.1: Thesis defense permanent link https://www.youtube.com/watch?v=0k5aQKMdXdM

Appendix G

Additional pictures



Appendix G.1: Chili-pepper plant at flowering stage



Appendix G.2: Chili-pepper plants transplantation



Appendix G.3: Traditional weeding



Appendix G.4: Field monitoring weather station



Appendix G.5: Manual weeding



Appendix G.6: Chili-pepper plants purchased from professional nursery



Appendix G.7: Irrigation basin



Appendix G.8: Yield measurement



Appendix G.9: Pest management products application



Appendix G.10: Fertilization tank



Appendix G.11: On farm nursery



Appendix G.12: Manure tea production container



Appendix G.13: Chili-pepper field



Appendix G.14: Chili-pepper field with cereal wind breaker belt