Évaluation ex ante des systèmes de culture innovants par modélisation agronomique et économique : de la conception à l'adoption ; cas des systèmes de culture bananiers de Guadeloupe

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EVALUATION EX ANTE DE SYSTEMES DE CULTURE INNOVANTS PAR MODELISATION AGRONOMIQUE ET ECONOMIQUE : DE LA CONCEPTION A L'ADOPTION

Cas des systèmes de culture bananiers de Guadeloupe

présentée et soutenue publiquement par

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Sommaire

Résumé

Face à la multiplication et la complexité croissante des objectifs assignées à l'agriculture, les méthodologies de conception et d'évaluation *ex ante* de systèmes de culture innovants font l'objet d'un effort de recherche très soutenu. Cependant malgré le foisonnement de recherches et de productions d'outils disciplinaires, peu de recherches d'interface ont été entreprises, ce qui limite les possibilités d'évaluations *ex ante* globales des systèmes innovants, de la conception à l'adoption par les agriculteurs. L'objectif de cette thèse est de contribuer à l'avancée de ces travaux, en proposant une méthode transdisciplinaire d'évaluation *ex ante* de systèmes de culture innovants basée sur la combinaison d'outils de modélisation issus de l'agronomie et de l'économie. A partir d'une analyse de la littérature actuelle et de ses forces et faiblesses, nous construisons une méthode originale qui se décompose en 4 étapes : i) modélisation de la diversité des exploitations et prototypage de systèmes innovants plus durables, ii) utilisation d'un modèle de culture pour simuler le fonctionnement biophysique des innovations dans les types d'exploitations, iii) évaluation des impacts de l'adoption sur le fonctionnement et les performances des types d'exploitation à l'aide d'un modèle bio-économique d'exploitation, iv) modélisation *ex ante* de l'adoption par les planteurs à l'aide d'un modèle économétrique.

La méthode est ensuite appliquée à la conception et à l'évaluation *ex ante* de prototypes de systèmes de cultures bananiers aux Antilles françaises, qui traversent actuellement une crise socio-économique et environnementale sévère. L'application de la première étape de la méthode a permis d'identifier 6 types d'exploitations très contrastés avec des problèmes de durabilité se déclinant différemment et de mettre au point 16 prototypes de systèmes innovants impliquant plante de couverture cultivées en association ou en rotation, nouvelles variétés de bananiers, et réduction de l'usage des intrants chimiques. La deuxième étape a montré que les performances agronomiques des prototypes peuvent varier considérablement d'un type d'exploitation à un autre, et que certains systèmes semblent très prometteurs sur le plan agronomique et environnemental. Cependant les modélisations réalisées en étape 3 et 4 montrent que d'une part, des innovations performantes à la parcelle peuvent poser des problèmes de trésorerie et de charge de travail à l'échelle de l'exploitation, et que d'autre part certaines innovations très prometteuses ont pourtant un taux d'adoption faible. Les résultats du modèle économétrique et des simulations réalisées en étapes 2 et 3 permettent alors de définir un ensemble de propositions d'action à destinations des acteurs de l'innovation et du développement en vue de maximiser les chances d'adoption de systèmes plus durables. Le dernier chapitre de cette thèse revient sur les forces et les faiblesses de la méthode et souligne sa généricité potentielle qui devrait donc permettre d'étendre son application à d'autres contextes afin d'assurer une meilleure adéquation entre les innovations produites par la recherche agronomique et les attentes des agriculteurs et de la société.

Abstract

Agricultural production is evolving towards systems able to provide multiple objectives in order to satisfy the complex concerns related to sustainability, therefore leading agricultural research to bear growing interest in the development of methodologies to allow the design and assessment of innovative cropping and farming systems able to fulfil these constraints. Although the number and the diversity of tools and concepts are increasing, only few transdisciplinary research have been done, therefore limiting the development of methodologies for integrated assessment from the design to the adoption of innovations by farmers.

The objective of this thesis is to propose a trandisciplinary method for ex ante assessment of innovative cropping systems in order to palliate this shortcoming in the current research. After a survey of available assessment methodologies, we propose an original method which is made of a four-step approach: i) modelling farm diversity and prototyping innovative cropping systems, ii) use of a crop model to simulate the biophysical impacts of innovations for the different farm types, iii) development of a bio-economic farm model for assessment of the impacts of the adoption of innovations at farm level, and iv) econometric modelling of adoption by farmers.

The method was then applied to the design and assessment of innovative cropping systems for banana production in the French West Indies, that are currently facing severe economic and environmental crisis. The first step led to the identification of six contrasting farm types and sixteen cropping systems prototypes, invoving rotation of banana with cover crop, intercropping, and regulation of pesticide use. The second step showed that the performances of innovation may differ greatly among fram types, and some systems appear to be promising from both agronomic and environmental critera. However simulations made in step 3 and 4 showed that promising innovations at field level maight have negative impacts at farm level while some promising innovation have low probability of adoption. Results of econometric model and bio-economic simulations made possible to define a set of proposals for local research and development stakeholders in order to improve the likelyhood of adoption of the innovations.

In the last chapter we present a critical analysis of the advantages and shortcomings of our approach underling the genericity of the methodology, and the potential extension of its application to other context, for better matching the innovations with society and farmers demands.

Introduction générale : une contribution aux recherches sur les méthodes d'évaluation ex ante de systèmes de cultures innovants

Un des enjeux de l'agriculture moderne est de nourrir la planète tout en pratiquant des modes de production durables, c'est-à-dire : productif ; respectueux des ressources naturelles, des écosystèmes, et de la santé humaine ; et acceptables pour les populations qui doivent en vivre.

En France, comme dans de nombreux pays, consécutivement à l'adoption par les agriculteurs d'un grand nombre d'innovations techniques, les cinquante dernières années ont vu les modes de production de l'agriculture se transformer profondément et accroître considérablement leur productivité. Parmi les principales innovations qui ont permis un fort accroissement de la productivité par hectare et par homme, on trouve la mécanisation, les fertilisants chimiques, les pesticides, les nouvelles variétés sélectionnées à haut potentiel de rendement, et plus récemment, les OGMs et l'agriculture de précision. La recherche agronomique publique et privée a grandement participé à ce processus d'innovation, en inventant des solutions à des problèmes qui étaient au cœur des politiques publiques de l'époque comme l'autosuffisance alimentaire nationale, la libération de main d'œuvre pour d'autres secteurs économiques, et la réduction du prix des aliments.

Cependant, à l'orée du troisième millénaire, force est de constater que l'agriculture est soumise à de fortes pressions évolutives qui amènent à devoir repenser les modes de production actuels (Meynard et al., 2006) :

- 923 millions de personnes sont sous-alimentées dans le monde, et nombreux sont les endroits où des prix agricoles trop élevés ou des rendements trop bas sont responsables de cette situation (FAO, 2008).

- La responsabilité de l'agriculture est avérée dans la dégradation de l'état de l'environnement à plusieurs niveaux (Millenium Ecosystem Assessment, 2005):
    - o dégradation de la qualité des eaux superficielles et souterraines (pollutions azotées et phosphorées, pollutions par les pesticides), des sols (contaminations par les pesticides, métaux lourds, érosion...), et de l'air (composés volatiles à l'échelle locale et gaz à effet de serre à l'échelle globale),
    - o perte de biodiversité (homogénéisation des paysages, pesticides, déforestation, etc.) et dérèglement de la biodiversité (apparition d'espèces envahissantes),
    - o épuisement des ressources non renouvelables (énergie fossile),
    - o augmentation des risques de catastrophes (inondations, coulée de boue…).

- Bien qu'elle puisse être soutenue par des politiques publiques (subventions, barrière douanière, etc.), qui elles-mêmes sont régulièrement remises en question, la compétitivité des exploitations agricoles se trouve affectée par un contexte de mondialisation des échanges qui agit à plusieurs niveaux :
    - o fluctuations aléatoires des cours mondiaux des produits agricoles,
    - o augmentation du coût des intrants, en particulier à cause de la raréfaction des ressources énergétiques et du contexte géopolitique mondial,
    - o mise en concurrence de pays exportateurs ayant des coûts de main d'œuvre très différents.

- Les évolutions des attentes des citoyens, consommateurs et de la demande des filières aval, poussent les modes de production à évoluer:
    - o demande croissante de certification, labellisation, contractualisation des modes de production fondée sur la traçabilité, en vue de garantir la qualité sanitaire, esthétique, et organoleptique des produits,
    - o demande de maintien d'un paysage « ouvert » et typique (vignes, vergers, bocage, marais, prairies, etc.),
    - o médiatisation croissante des débats sur les pratiques agricoles (exemple : pesticides, OGM, bien être animal) qui ouvre à toute la société la sphère des personnes se donnant un droit de regard sur les modes de production.

- Et enfin, le réchauffement de la planète affecte des modes de production qui sont eux-mêmes partiellement responsable du changement climatique :
    - catastrophes naturelles qui affectent la productivité des cultures : augmentation de la fréquence et de l'intensité des sécheresses, inondations, cyclones,
    - modes de production qui contribuent au réchauffement climatique par la libération de gaz à effets de serre:
        - fermentation entérique des animaux d'élevage et gestion des effluents dans un contexte de fort développement de l'élevage en relation avec l'évolution des modes alimentaires,
        - déforestation pour mise en culture,
        - augmentation de la fréquence du travail du sol, fertilisation azotée.

Ce constat déjà long mais pourtant partiel, au delà de révéler la nécessité croissante d'innover qui s'impose aux agriculteurs sous l'effet de changements nombreux, est également révélateur de l'ambivalence des innovations (Papy, 2004) : innovation ne rime pas forcément avec progrès social. Par ailleurs ce tableau révèle aussi la complexification du cadre de contraintes dans lequel les agriculteurs doivent prendre leurs décisions pour innover... ou décider de conserver leur système. En effet, il ne s'agit pas seulement d'inventer des solutions techniques, il faut qu'elles soient adaptées aux exigences du marché, de la société, du consommateur mais aussi adoptées par les agriculteurs. Le faible développement des systèmes de culture biologiques en France en est une bonne illustration.

On peut dès lors faire l'hypothèse que si on évalue les systèmes de culture innovants dès la phase de conception on peut alors augmenter les chances qu'ils soient adoptées (en évaluant la conformité des innovations avec les attentes, contraintes et préférences des agriculteurs) et efficaces (en évaluant la conformité des innovations avec les attentes de la société). Cependant, comme nous le verrons plus tard, les travaux actuels sont relativement cloisonnés entre différents domaines disciplinaires qu'il est nécessaire de combiner. Ainsi on comprend aisément pourquoi un des challenges scientifiques de la recherche agronomique contemporaine est le développement de méthodes systémiques et transdisciplinaires d'évaluation *ex ante* des innovations en termes d'effets économiques, sociaux et environnementaux, au niveau de la parcelle, de l'exploitation agricole et du territoire.

L'objectif de cette thèse est de contribuer à l'avancée de ces recherches, en concevant et testant une méthode basée sur la combinaison de différents outils de modélisation issus des sciences agronomiques et des sciences économiques et sociales.

Dans le premier chapitre nous présentons un état de l'art sur les méthodes d'évaluation *ex ante* de systèmes de culture innovants et nous en discutons les limites. Nous en déduisons les objectifs assignés à cette thèse, proposons une méthode globale en quatre étapes, puis présentons le support sur lequel la méthode a été testée, à savoir les systèmes de cultures bananiers aux Antilles. Les quatre chapitres suivants présentent successivement les 4 étapes de la méthode. Ils sont présentés sous la forme d'articles scientifiques en anglais qui sont soumis à publication dans des revues internationales, et tous précédés d'une transition avec le chapitre précédent qui resitue la position des travaux au sein de la démarche globale. Le dernier chapitre formule des recommandations agronomiques et politiques pour l'exemple traité, puis discute des intérêts, des limites et de la généricité de la méthode proposée en suggérant des pistes d'amélioration et des questions de recherche à approfondir.

1. Problématique, objectifs et méthode

L'objectif de ce chapitre est triple. Premièrement, nous dressons un état de l'art de la recherche internationale sur les méthodes d'évaluation *ex ante*[1] de systèmes de culture[2] innovants[3]. Nous en déduisons les limites des recherches actuelles et définissons l'objectif général de cette thèse en vue de contribuer à leur amélioration. Nous proposons ensuite une nouvelle méthode d'évaluation *ex ante* de systèmes de culture innovants afin de répondre aux objectifs identifiés. Enfin nous présentons le support sur lequel la méthode a été testée, c'est à dire les systèmes bananiers aux Antilles.

1.1. Etat de l'art des méthodes d'évaluation *ex ante* de systèmes de culture innovants

Nous nous appuierons ici principalement sur les synthèses réalisées par Loyce et Wery (2006), et Meynard et al. (2006). Bien que le champ couvert par cette partie soit principalement celui des méthodes d'évaluation *ex ante* de systèmes de culture innovants, il recoupe aussi souvent le champ des évaluations *ex post* et le champ des méthodes de conception.

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[1] *Ex ante* : s'oppose à *ex post*, qui veut dire rétrospectif. On parle d'évaluation *ex ante* d'une innovation lorsque celle-ci n'est pas encore adoptée, et qu'on ne peut donc pas en regarder les effets en les observant sur les systèmes étudiés (exploitation agricole, région, filière).

[2] Système de culture (*cropping system*) : la notion de système de culture s'applique à la manière de conduire des cultures et des successions culturales en interaction avec un milieu biophysique et un milieu socio-économique. Ces systèmes peuvent être étudiés à des échelles variées, de la parcelle à l'ensemble des parcelles d'une exploitation agricole ou d'une région (Meynard, 1992). On parle de système (du grec *sustêma*, ensemble) car il s'agit d'une combinaison complexe d'éléments (des techniques) réunis de manière à former un ensemble fonctionnant de manière unitaire et en interaction permanente.

[3] Innovation : Dans le sens commun l'innovation décrit une invention qui introduit un degré de changement par rapport à l'existant. Dès lors, on dit d'un objet qu'il est innovant lorsqu'il introduit un degré de changement par rapport à l'existant. Néanmoins, en sociologie, le terme « innovation » désigne souvent un processus qui va d'une invention à sa diffusion (Papy, 2004). Dans cette thèse nous retiendrons la première définition.

Cela se justifie car d'une part, il n'est pas exclu que des outils principalement utilisés *ex post*, soient aussi pertinents dans le cadre d'évaluations *ex ante*, bien qu'ils ne le soient pas aujourd'hui. Qui plus est la littérature sur les évaluations *ex post* semble bien plus abondante que la littérature sur les évaluations *ex ante*. C'est pourquoi, lors de notre bibliographie initiale, nous sommes aussi allés explorer le champ des analyses *ex post.*

D'autre part conception et évaluation de systèmes innovants sont bien souvent indissociables car toute activité de conception fait usage d'étapes d'évaluation, et inversement on conçoit souvent des innovations à partir de résultats d'évaluation. Il est à souligner que les deux sont d'ailleurs souvent utilisés itérativement pour réaliser des boucles de progrès dans le cadre de programme d'amélioration des performances des systèmes de culture.

La suite de cette section est décomposée selon trois niveaux d'échelle : parcelle, exploitation, territoire.

1.1.1. L'évaluation à la parcelle des performances du champ cultivé

Ces méthodes permettent principalement d'évaluer les performances agronomiques et environnementales des systèmes innovants, et dans une moindre mesure les performances économiques. Pendant longtemps l'expérimentation a été le seul point d'appui de l'agronome pour l'évaluation des systèmes de culture innovants. Celle-ci consiste en des essais factoriels en station expérimentale sur des parcelles de taille réduite. Si ces méthodes se sont révélées efficaces pour tester un ou quelques facteurs en vue d'améliorer un ou quelques critères (le plus souvent le rendement seul), elle s'avèrent insuffisantes car trop longues et trop coûteuses pour tester des systèmes très innovants dans un climat variable et des sols diversifiés. Cependant certains systèmes très innovants peuvent être évalués expérimentalement sur de nombreux critères dans le cadre d'expérimentation « système ». Lançon et al. (2007) évaluent ainsi un itinéraire technique[4] du cotonnier (*Crop Management System*[5]) très innovant qui permet de répondre à un ensemble cohérent d'objectifs et de contraintes, mais avec une grande adaptation par rapport à l'endroit où le prototype a été développé et évalué.

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[4] Itinéraire technique: combinaison logique et ordonnée de techniques appliquées à une culture (Sebillotte, 1974). La notion d'itinéraire technique recouvre le même contenu que la notion de système de culture, mais appliquée à un seul cycle cultural ; ce concept a été transposé aux cultures pérennes et aux troupeaux, pour désigner l'ensemble des actes techniques appliqués à un verger ou à un lot d'animaux sur une année.

[5] La traduction anglaise du concept d'itinéraire technique par *Crop Management System* a été proposé par Rapidel et al. (2006).

D'autres approches dites « participatives » ont été développées depuis le milieu des années 90 par des chercheurs de l'ICRAF (*participatory research*) et des chercheurs de l'université de Wageningen (*prototyping*). Elles comportent des méthodes impliquant évaluation expérimentales des innovations sur des exploitations réelles, on parle alors d'évaluation « *on farm* ». La plupart du temps ces méthodes incluent une phase préalable de conception de l'innovation par prototypage. Dans les approches participatives de l'ICRAF les agriculteurs participent au choix des innovations (Franzel et Scherr, 2002) alors que dans l'approche hollandaise le prototypage se fait avec des experts (Vereijken, 1997 ; Stoorvogel, 2004). Ces approches ont l'avantage d'informer simultanément sur les performances biophysiques, les performances économiques et le « potentiel d'adoption » des innovations par les agriculteurs. Cependant ces méthodes restent coûteuses et partielles, en ce sens qu'elles ne portent que sur une partie de l'exploitation et sont limitées à des panels d'agriculteurs restreints (pour le moins à ceux qui acceptent de participer), ce qui augmente le risque de biais dans la conception et l'évaluation du système.

La modélisation numérique du fonctionnement du champ cultivé est une méthode alternative à l'expérimentation au champ en plein développement. Le développement de ces méthodes est récent, car il a été rendu possible, notamment par l'amélioration de la capacité de calcul et de stockage des ordinateurs. De tels modèles permettent d'évaluer de grands nombres de systèmes de culture innovants, sur de nombreux critères ou indicateurs, dans une gamme de contextes biophysiques variés (Keating et al., 2003 ; Tixier et al., 2008a). On parle d'expérimentation « *in silico* ». Certains modèles permettent même la génération automatique et en grand nombre de combinaisons innovantes qui sont ensuite automatiquement évaluées et triés en fonction des objectifs recherchés (Loyce et al., 2002a ; 2002b ; Dogliotti et al., 2004). Ces modèles sont de plus en plus souvent couplés à des modèles décisionnels et permettent d'optimiser des règles de décision et d'en tester de nouvelles (Bergez et al. 2001; Bergez et al. 2002; Maton et al. 2007). Ces approches possèdent néanmoins quelques limites : d'une part elles prennent peu en compte la diversité des contextes économiques et techniques dans lesquels devront s'insérer les innovations, et d'autres part, elle sont le plus souvent limitées aux capacités du modèle biophysique et donc restreintes à des gammes d'innovations de moindre ampleur que celles pratiquées par les agriculteurs pionniers.

Toutes ces approches sont basées sur des indicateurs qui correspondent soit à des valeurs mesurées directement (par exemple le rendement, ou la teneur en nitrate des eaux de drainage), ou bien sur des indicateurs plus sophistiqués qui combinent plusieurs type de données qui peuvent être mesurées au champ, simulées avec des modèles, ou fournies par des experts (Bockstaller et al., 2008 ; Pervanchon et al., 2005 ; Tixier et al., 2007c).

1.1.2. L'évaluation à l'échelle des exploitations

Les analyses du type « coût-bénéfice » (*cost benefit analysis*) réalisées à l'échelle de l'exploitation (voir par exemple Addy, 1984, Current *et al.*, 1995) constituent la base incontournable de toute évaluation *ex ante*, mais utilisées seules elles sont insuffisantes car elles ne permettent pas de tenir compte des conditions d'adoption des innovations, qui dépendent d'autres critères que le revenu, comme par exemple la compatibilité entre l'innovation et les contraintes des agriculteurs et l'adéquation avec leurs objectifs personnels.

A cette fin, en France, des chercheurs du département SAD de l'INRA ont proposé un concept intéressant : le concept de « marge de manœuvre » des agriculteurs pour adopter des innovations. En utilisant le concept de modèle d'action (Cerf et Sebillotte, 1988), qui permet de reconstituer de manière systémique le processus de décision des agriculteurs qui a présidé à la genèse de leur système de culture, le concept de marge de manœuvre permet d'identifier des points de blocage organisationnels. Ces approches ont montré par exemple que la logique dont procède la suite des interventions culturales sur une parcelle ne résulte pas de seules considérations biophysiques de conduite de la parcelle, mais de niveaux supérieurs de gestion comme la sole et l'ensemble des cultures entre lesquelles l'agriculteur fait des arbitrages d'affectation des moyens de production à l'échelle de l'exploitation (Aubry, 1998, Papy et al., 2001). Ces approches peuvent être intéressantes car, une fois reconstitué le processus de décision des agriculteurs pour les décisions qui vont être affectées par l'introduction de l'innovation, elles permettent d'évaluer *ex ante* les marges de manœuvres des agriculteurs pour adopter ces innovations. Par exemple Joannon et al. (2005) évaluent les marges de manœuvres des agriculteurs en terme de calendrier de travail disponible pour semer une plante de couverture afin de limiter le ruissellement érosif entre les cycles de deux cultures.
Cependant, cette approche a été principalement appliquée à des innovations incrémentales de faible magnitude, étant limitée par la complexité de la modélisation simultanée d'un grand nombre de décisions d'action (Aubry et Michel-Dounias, 2006).

Une approche intéressante d'évaluation des innovations à l'échelle des exploitations a été également proposée par l'école agronomique hollandaise avec les modèles bio-économiques d'exploitations (*Bio-Economic Farm Model*, BEFM). Pour une bonne revue de ces modèles on peut se référer à Janssen et van Ittersum (2007). Ces modèles de programmation linéaire modélisent le processus de décision des agriculteurs selon un processus de maximisation du revenu sous contraintes de ressources limitantes. Ils permettent en sortie d'avoir le choix d'affectation de l'usage de la surface de l'exploitation par l'agriculteur. Ces modèles permettent dès lors de tester la viabilité économique des innovations et d'en prévoir l'adoption sous différents scénarios de prix, de politiques, et de conditions géographiques et climatiques (Abadi Ghadim, A.K., 2000 ; ten Berge et al., 2000).

Ces modèles présentent néanmoins quelques faiblesses. Une limite majeure de ces modèles est qu'ils sont faits pour choisir un système de culture optimal par rapport aux contraintes et à une fonction objectifs définie par le modélisateur mais pas pour évaluer les impacts de plusieurs systèmes dans le contexte de l'exploitation. Ensuite, ils ne modélisent pas de manière mécaniste les processus biophysiques, et qui plus est ils sont de ce fait assez consommateurs en données d'entrées et en expertise sur les innovations, qui ont donc un poids prépondérant dans les analyses. De plus ceci rend difficile leur utilisation dans le cadre de programmes de prototypage d'innovations (Sterk et al., 2007). Par ailleurs, bien que les simulations puissent être enchaînées, ces modèles sont statiques, ce qui empêche d'aborder des processus se jouant à des pas de temps courts, par exemple au niveau des tensions sur les ressources en cours de cycle de culture. Enfin ces modèles sont déterministes et bien qu'ils prennent explicitement en compte les contraintes et les objectifs des agriculteurs, ils ne permettent pas de considérer d'autres facteurs importants comme par exemple les attitudes personnelles des agriculteurs face à l'innovation et leur insertion dans des réseaux de communications. Enfin il ne permettent pas de quantifier de manière endogène (c'est-à-dire du point de vue de l'agriculteur) le poids des contraintes et objectifs dans la décision d'adoption, puisque ceux-ci sont implicitement fixés en entrées par les concepteurs du modèle.

Les modèles économétriques de choix discret permettent de contourner cette difficulté, de par leur capacité à identifier de manière quantitative des profils de préférences pour l'innovation au regard des caractéristiques de l'innovation d'une part et des agriculteurs d'autre part. L'analyse économétrique des préférences individuelles est principalement issue du marketing quantitatif et a pour objet l'étude des choix individuels. Elle se fixe pour objectif de trouver des moyens d'observation et de mesure de la variabilité existant dans les déterminants des choix, en essayant d'utiliser le maximum d'informations sur l'hétérogénéité de ces choix (Lecocq et Simioni, 2005). Pour cela elle se base sur un cadre conceptuel qui lui permet d'identifier les déterminants des choix individuels. Ce cadre est fourni par l'économie et la psychologie en supposant que les individus agissent de telle sorte que leur choix est celui qui leur procure soit la plus grande utilité (économie) soit la plus grande satisfaction (psychologie) parmi l'ensemble des alternatives auxquelles ils sont confrontés. La **figure 1** illustre cette démarche et donne la structure de base des modélisations utilisées dans la littérature sur les choix discrets. Cette représentation montre que les caractéristiques (des innovations et des agriculteurs par exemple) sont reliées de manière structurelle à l'utilité (considéré comme une variable latente, car non observable directement) à travers une fonction, et que c'est les choix observés qui permettent de mesurer les paramètres de cette fonction.

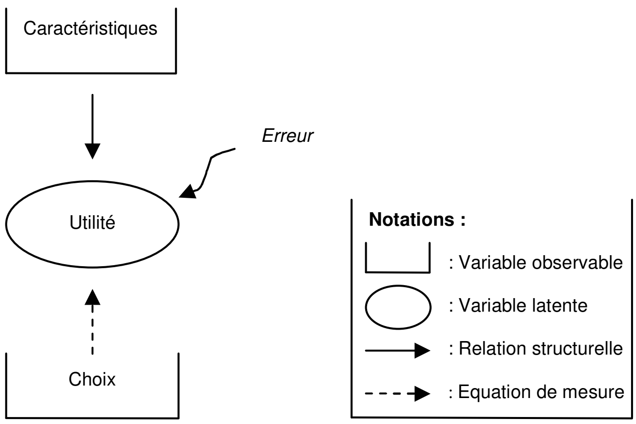


Figure 1 : structure générale des modèles de choix (Lecocq et Simioni, 2005)

Différents modèles plus ou moins sophistiqués peuvent être utilisés : modèles Logit, Probit ou Tobit (en fonction de l'hypothèse faite sur la loi que suit les résidus du modèle), utilisant des profils de réponse binomial (*e.g.* adoption ou non adoption), multinomial (*e.g.* choix d'une innovation parmi 5), ou de classement (*e.g.*, classement de 5 innovations par ordre de préférence) et qui peuvent être emboîtés (on suppose que la décision peut se décomposer en plusieurs sous-étapes emboîtées), conditionnels (modèle qui permet d'estimer les probabilités de choix d'une innovation conditionnellement à ses caractéristiques), etc. Nous ne les détaillerons pas ici, mais ces approches font l'objet de recherches actives en économie (Thomas, 2006).

Une part très importante de la littérature sur l'adoption d'innovations en agriculture est basée sur l'utilisation de ces modèles de choix discret, très majoritairement dans le cadre d'études *ex* *post* des déterminants de l'adoption (voir par exemple pour des revues: Feder and Umali, 1993 ; Abadi Ghadim and Pannell, 1999 ; and Marra et al., 2003 ; et pour des études de cas: Adesina et al., 1995 ; 2000 ; 2002). Ces études mettent en évidence l'existence de comportements des agriculteurs différenciés face à l'innovation, en fonction des attributs de l'innovation (ses caractéristiques et ses performances), des ressources de l'exploitation, du « capital humain » de l'agriculteur (âge, niveau d'éducation, appartenance à des réseaux sociaux, etc.), et de ses attitudes personnelles, en particulier face au risque. Ces études permettent également d'aborder le rôle des politiques de soutien pour favoriser l'adoption d'une innovation (Ducos and Dupraz, 2007). Quelques études *ex ante* ont été réalisées (e.g. Batz et al, 2007) mais sur un nombre très restreint d'innovations incrémentales, et donc pas sur des systèmes entiers, voire plusieurs systèmes en même temps. Bien souvent les innovations sont décrites très simplement avec peu de précision sur les systèmes de culture et sur leurs performances supposées dans les exploitations, lorsque celles-ci ne sont pas construites artificiellement dans le cadre de procédure de génération de plans d'expérience équilibrés dans des études économétriques de *choice experiment* (Breustedt et al., 2008). Une autre limite dans l'utilisation de ces modèles qui est pointée dans la littérature est que bien souvent elles mettent l'accent sur certains déterminants très particuliers comme les attitudes face au risque, les attributs des innovations ou les facteurs sociaux, mais sans jamais considérer ensemble une large gamme de facteurs d'adoption potentiels.

1.1.3. L'évaluation à l'échelle des territoires

L'évaluation à l'échelle des territoires est nécessaire à plus d'un titre. Elle est indispensable pour évaluer i) les processus sociologiques de diffusion d'innovations, ii) les impacts des systèmes de cultures sur les ressources naturelles, iii) les impacts sur les écosystèmes et iv) les processus économiques au sein des filières qui conditionnent les performances et favorisent l'émergence des innovations. Tous ces processus ont une inscription spatiale qui dépasse le cadre de l'exploitation et amène à s'intéresser aux territoires. De fait, ces processus d'adoption et d'évaluation sont nécessairement multi-acteurs et multi-décideurs.

L'agriculteur peut être considéré comme un être social, parce qu'il participe à des collectifs d'échanges techniques, des réseaux, des organisations (Papy, 2004 ; Compagnone, 2004). Au sein de ces réseaux, il est influencé et influence, et les décisions qu'il prend dépendent pour partie des groupes sociaux auxquels il appartient. Cependant nous n'avons trouvé aucune étude sociologique portant sur l'évaluation *ex ante* d'une innovation, toutes les études étant le plus souvent soit réalisées *ex post*, soit complètement déconnectées d'un questionnement d'évaluation d'innovation agronomique. La plupart de ces études sont réalisées par enquêtes et ont quelques fois aussi recours à de la modélisation multi-agent (Houdart et al., 2007), mais elles sont toujours déconnectées de la réalité des processus agronomiques au niveau du champ cultivé.

De nombreuses questions environnementales se posent à des échelles territoriales comme par exemple les problèmes de pollutions de nappes et de rivières en pesticides et en nitrates en zone de monoculture intensive comme la vigne en Languedoc ou la banane aux Antilles, ou l'étude des désagréments liés à la qualité de l'air lors de l'épandage d'effluents d'élevage en région d'élevage intensif. Ces processus sont le plus souvent abordés avec des modèles biophysiques spatialisés sous SIG (par exemple, Gemitzi et al., 2008), et validés avec des données expérimentales.

Les travaux sur les impacts à l'échelle des écosystèmes sont moins nombreux mais en pleine expansion. Ceci peut s'expliquer d'une part par la complexité et le nombre des processus en jeu, les limites dans l'intégration informatique des modèles, et d'autre part par la forte demande sociétale en la matière. Certains travaux ont permis par exemple d'évaluer *ex ante* les impacts de l'introduction d'une innovation à l'échelle d'un paysage, par exemple le risque de flux de transgènes entre une culture OGM et une espèce naturelle (Colbach et al., 2001). A cette échelle, l'innovation est vue comme une nouvelle combinaison spatiale de systèmes de culture.

Enfin de nombreux travaux en économie de l'innovation visent à étudier l'innovation à l'échelle des filières ou d'une nation tout entière. Ces travaux visent d'une part à évaluer *ex ante* quels sont les bénéfices que pourront tirer d'une innovation les différents acteurs d'une filière, et d'autre part à étudier les conditions économiques d'émergence d'une innovation en termes de filières et de réseaux d'acteurs économiques.
La littérature en la matière est très abondante. De nombreuses études de ce type ont par exemple été conduites sur l'adoption des nouvelles variétés OGM (voir par exemple Lemarié et al., 2001 ; Alston, et al. 2002). Ces études sont très utiles pour éclairer les décideurs

politiques dans la promotion d'une innovation puisqu'elles permettent d'évaluer *ex ante* les coûts et bénéfices associés à son adoption à différents niveaux de la filière ou de la nation.

La réussite d'une innovation dépend également de facteurs organisationnels, informationnels et contractuels à l'échelle des acteurs des filières concernées par une innovation. A ce titre la revue de 50 ans d'innovations en agriculture sur les conditions de développement et de réussite des innovations de Joly et Lemarié (2000) est très révélatrice. Ces auteurs montrent que le processus d'innovation implique de nombreux réseaux d'acteurs et qu'une innovation majeure n'existe pas *ex ante*, elle se construit par catalyses successives, au cours du processus de diffusion. In fine, c'est la chaîne: recherche, règlementation, agriculture, conseil agricole, firmes amont, firmes aval, politiques agricole, consommateurs, etc. qui conditionne la rupture technologique. Le développement économique d'une innovation ne peut se faire que par la création d'acteurs collectifs ou publics susceptibles d'assurer des fonctions communes comme (1) recherche technique, ou opérations d'achat, de vente, de conseil, inaccessibles à des producteurs individuels, (2) accords de coopération économique et de normalisation qui permet une stabilisation des pratiques et des produits, (3) des systèmes nationaux ou communautaires d'aides publiques à la production ou à l'investissement.

1.2. Analyse critique de l'état de l'art et définition de l'objectif scientifique de la thèse

Dans la section précédente nous nous sommes efforcés de dresser une vue ensemble des différentes démarches développées par la recherche pour l'évaluation des systèmes de culture innovants. Un regard transversal et critique sur cet état de l'art montre que :

- Les disciplines concernées par l'évaluation des systèmes de culture innovants vont de l'agronomie *stricto sensu*[6] aux sciences humaines (économie et sociologie) en passant par les sciences de l'environnement (écologie, hydrologie, etc.)
- Le recours à la modélisation numérique est abondant dans toutes les disciplines, hormis la sociologie qui semble moins impliquée dans cette voie.
- La diversité des exploitations est trop faiblement prise en compte.
- Il existe un grand cloisonnement entre disciplines.

[6] Agronomie stricto sensu : discipline scientifique qui a pour objet d'étude premier le champ cultivé, considéré à la fois comme objet physique et comme objet d'application d'un raisonnement : celui des techniques par l'agriculteur (Doré, 2006).

Nous allons maintenant développer ce dernier point qui nous semble être crucial pour positionner l'originalité de notre travail et qui avait déjà été pointé par Thornton et al. (2003) et Mercer (2004).

En première approche on pourrait dire que d'une part les agronomes *stricto sensu* font peu cas des réalités économiques qui environnent leur objet d'étude et de leur diversité, ce qui peut biaiser l'évaluation de l'impact des innovations (notamment sur leurs performances économiques) et la probabilité de leur adoption (en sous-estimant le poids de certaines contraintes de l'exploitant qui rendent l'adoption de l'innovation improbable). On pourrait schématiser en disant que visant une certaine généralité, les méthodes actuelles négligent plus ou moins les détails des réalités locales. D'autre part les disciplines plus en aval qui s'intéressent aux conditions d'acceptation et d'émergence des innovations semblent très imprécises sur les bases agronomiques de leur scénarios, parce qu'elles considèrent juste les innovations comme des technologies isolées sans considérer les adaptations que leur adoption vont nécessiter au niveau du système de culture, et parce que leurs performances sont souvent décrites de manière peu précise (description non quantitative, pas de prise en compte de la diversité possible des performances selon le contexte biophysique et économique de l'exploitant).
Dans l'état actuel des recherches, ces deux champs de disciplines sont donc *ipso facto* difficilement connectables en un seul corpus systémique.

Chaque discipline produit des connaissances et des outils pertinents pour des questions spécifiques à la discipline, mais chacune souffre d'une prise en compte partielle de l'innovation agronomique dans ce qu'elle a de plus systémique, entre la dimension biophysique à la parcelle et l'adoption à l'échelle d'un territoire. La profusion de recherches disciplinaires sur les outils contraste avec la rareté des recherches sur des méthodes combinant ces outils dans le cadre d'une approche systémique. Bien que toutes ces disciplines aient en commun tout ou partie d'un objet d'étude (les systèmes de culture), elles le voient à travers un prisme différent dans leur questions de recherche: pour l'une il est un « ensemble de techniques qui sont appliqués sur une parcelle », pour un autre il est soit « un problème de pollution diffuse à l'échelle d'un bassin-versant », soit « une innovation économique pour un pays», soit « une décision individuelle d'investissement sous contraintes », soit « l'objet d'un comportement sociologique ». Chaque discipline à ses concepts, ses courants de pensées, ses outils propres, qui sont de ce fait difficilement accessibles aux seuls spécialistes disciplinaires. Comme le dit Sebillote (2006), *« l'une des raisons de la trop lente avancée des travaux sur le développement durable est en partie liée à l'insuffisance de recherches transdisciplinaires ».* Sebillote, agronome *stricto sensu*, va plus loin en disant : « *Les approches transdisciplinaires supposent une grande ouverture aux autres disciplines et aux problèmes des sociétés. (…) Si les spécialistes que nous formons sont incapables de comprendre les présupposés épistémologiques des autres chercheurs, donc de savoir comment ils pensent, comment espérer que l'on traite correctement du développement durable ?»*

Ce cloisonnement entre sciences agronomiques, sciences de l'environnement et sciences humaines et sociales nuit à l'opérationnalité des résultats de la recherche sur l'innovation dans les systèmes agricoles.

Il est donc urgent d'entreprendre des recherches portant sur le développement de méthodes transdisciplinaires qui permettent d'évaluer, les systèmes de culture au cours du processus d'innovation, en combinant les regards des sciences agronomiques, des sciences environnementales et des sciences économiques et sociales. Cela impose de se pencher en premier lieu sur les méthodes de couplage ou d'utilisations combinées des différents outils disciplinaires, et en particulier les modèles numériques qui semblent incontournables pour appréhender la durabilité dans son caractère multicritères et multi-échelles.

C'est ce que nous avons tenté de faire dans cette thèse en se fixant comme objectif :

Concevoir et tester une méthode d'évaluation *ex ante* de systèmes de culture innovants plus durables, par combinaison de différents outils de modélisation issus de l'agronomie et des sciences économiques et sociales; de la conception à l'adoption par les agriculteurs à l'échelle d'un petit territoire agricole.

1.3. Proposition d'une méthode transdisciplinaire d'évaluation *ex ante*

L'objectif de ce paragraphe est de présenter une méthode globale en présentant ses entrées, ses sorties et ses contours. Elle comporte 4 étapes principales qui seront chacune détaillées et mises en œuvre sur un exemple dans les chapitres 2 à 5.

Pour contribuer à l'objectif général formulé ci-dessus, dans le cadre limité d'une thèse, nous avons restreint le cadre de notre intervention à :

- l'échelle parcellaire et celle de l'exploitation (incluant le comportement de l'exploitant), l'échelle territoriale étant abordée seulement à travers la prise en compte de la diversité régionale des exploitations,
- couplage de modèles agronomiques (modèle biophysique de culture, modèle de gestion technique), modèle bio-économique d'exploitation et modèle économétrique d'adoption.

Ainsi nous ne traiterons pas ou peu des éléments suivants et donc n'utiliserons pas les modèles qui sont appropriés à leur étude :

- impacts des innovations sur les processus hydrologiques et écosystémiques,
- conditions d'adoption des innovations inhérentes aux organisations de filière (approvisionnement en intrants, marchés, coordination entre acteurs, etc.),
- des processus sociologiques de diffusion de l'innovation au sein de l'ensemble des exploitations du territoire.

Nous précisons que certains aspects des deux derniers points ci-dessus seront tout de même abordés dans la modélisation économétrique de l'adoption présentée dans le chapitre 5.

Le premier travail réalisé dans le cadre de cette thèse a été de construire à partir des briques éparses de la littérature disciplinaire une méthode générique de conception et d'évaluation *ex ante* de systèmes de culture innovants. Une vue d'ensemble de cette méthode que nous avons construite et que nous proposons est présentée dans la **figure 2**.

La méthode permet de choisir des systèmes innovants, de les évaluer sur la base de leurs performances agronomiques, environnementales, technico-économiques, et de leur acceptabilité par les agriculteurs, en tenant compte tout au long de cette démarche de la diversité des exploitations à l'échelle régionale. Cette dernière est modélisée par une typologie d'exploitations. Pour cela elle propose l'utilisation combinée et/ou le couplage de 4 types de modèles : une typologie d'exploitation[7], un modèle de culture, un modèle d'exploitation, et un modèle économétrique d'adoption.

[7] Nous considérerons la typologie d'exploitation comme un modèle conceptuel de la diversité des exploitations à l'échelle régionale, qui peut être implémenté informatiquement dans une base de données.

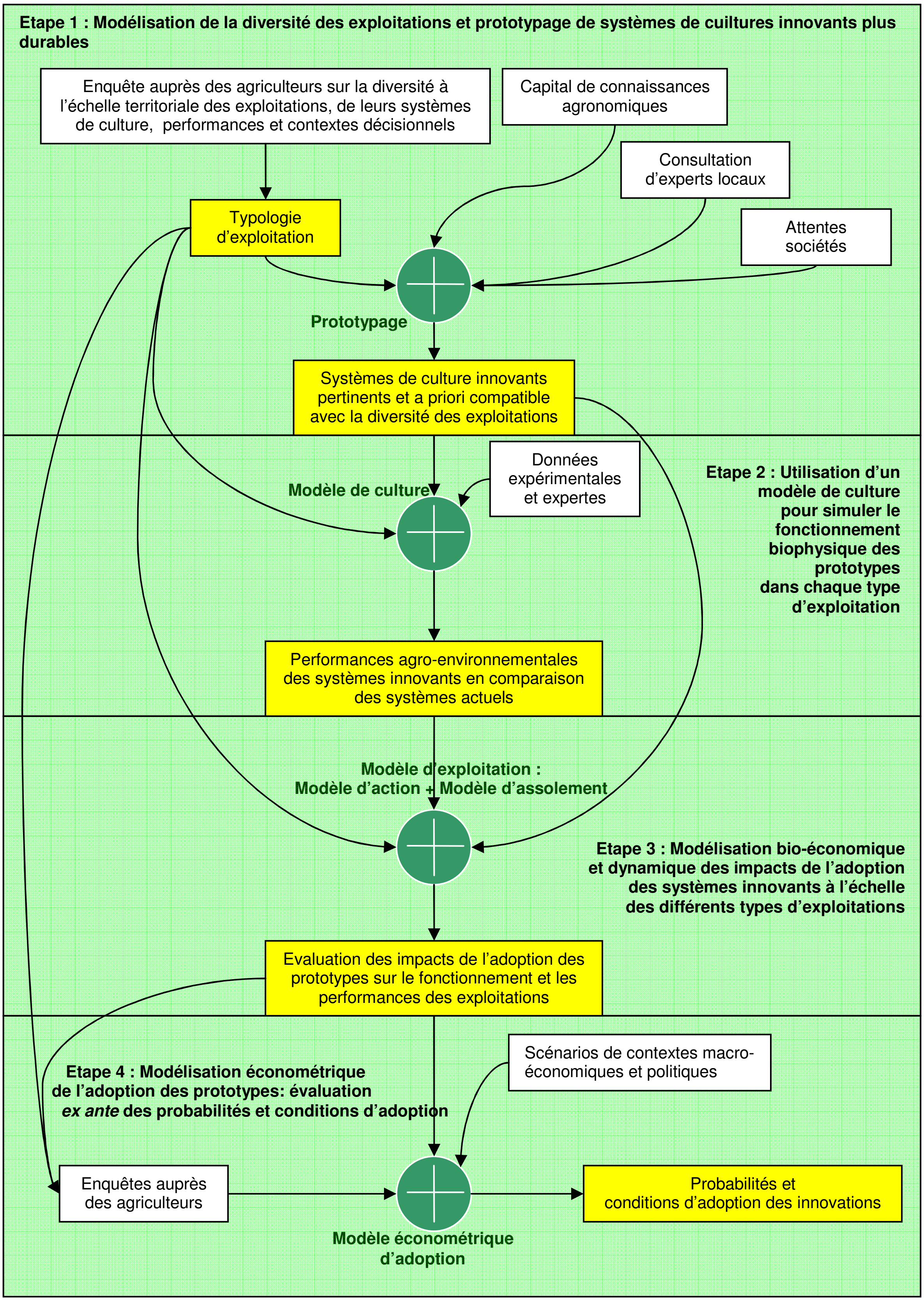


Figure 2 : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

A partir d'une enquête approfondie sur un échantillon restreint d'exploitations et une démarche de prototypage avec des experts, **l'étape 1** fournit une typologie d'exploitation et un « pool » de prototypes de systèmes de culture innovants en s'assurant de la pertinence et de la compatibilité *a priori* des innovations avec la diversité des situations observées sur le terrain.

Un modèle de culture est utilisé dans **l'étape 2** en prenant en compte les caractéristiques biophysiques et techniques de chaque type d'exploitation (système de culture mis en œuvre, pression parasitaire, type de sol, climat) afin d'évaluer les performances agronomiques et environnementales des prototypes et simuler leur comportement biophysique sur les différentes situations.

Un modèle d'exploitation est développé et utilisé dans **l'étape 3** afin de simuler les impacts techniques et économiques des prototypes à l'échelle des exploitations. Ce modèle, qui intègre le modèle utilisé dans l'étape 2, prend également en compte les caractéristiques techniques et économiques de chaque type d'exploitation (gestion du parcellaire de l'exploitation, coût de main d'œuvre, temps de travaux, etc.).

Enfin les résultats des simulations bio-économiques sont utilisés dans **l'étape 4** pour construire une enquête sur un échantillon important d'exploitants visant à estimer un modèle d'adoption générique des prototypes de systèmes de culture innovants. Dans cette dernière enquête les impacts des innovations sont aussi différenciés par type d'exploitation, conformément aux simulations de l'étape 3.

L'évaluation proposée dans cette méthode est centrée sur l'échelle de l'exploitation et de l'exploitant. Cette posture peut se justifier par le fait que l'agriculteur est le décideur unique de son activité, et qu'il est donc fondamental d'évaluer les chances d'adoption des innovations si l'on veut prétendre améliorer la durabilité globale des systèmes de culture à l'échelle territoriale. L'application de toute la méthode à tous les types d'exploitations permet ensuite au besoin de passer à une évaluation à l'échelle supérieure, celle du territoire, à travers une pondération des critères par la représentativité populationnelle ou spatiale de chaque type d'exploitation.

Le rôle de la typologie est clé dans la méthode car elle traverse toutes les étapes de la méthode. Cette posture de recherche propose de revoir le rôle des approches typologiques actuelles pour modéliser la diversité des exploitations (Capillon, 1993 ; Landais, 1998), qui n'ont généralement pas été conçues pour catégoriser les problèmes de mise en oeuvre et d'effets de techniques innovantes, ni de paramétrages de modèles biophysiques ou économiques.

De la même manière, bien que cela n'ait pas encore été réalisé, du moins à notre connaissance, nous utiliserons un modèle économétrique de manière originale, de par notre position *ex ante*, de par la précision des description des impacts des innovations faites aux agriculteurs (description systémique, quantitative et différenciée), et de par l'ambition de modéliser conjointement un nombre important d'innovations qui sont de nature très diverses.
Du point de vue de l'agronomie, l'apport de l'économétrie réside dans le fait qu'elle permettra d'une part de fournir un ensemble de recommandations pour améliorer la conception des innovations afin de maximiser leur chances d'adoption, et d'autre part de fournir dans le cadre d'une évaluation multi-critère une pondération des critères de performances agronomiques *endogène* aux préférences des agriculteurs, et non *exogène* comme c'est souvent le cas avec des pondérations à dire d'experts.

1.4. Application de la méthode au cas des systèmes de culture bananiers en Guadeloupe

La méthode que nous venons de présenter a été appliquée à l'exemple des systèmes de culture bananiers en Guadeloupe. Pour les besoins de l'étude le modèle économétrique a aussi été estimé en utilisant des données collectées auprès de planteurs de Martinique. Bien que présentant certaines différences, la culture de la banane peut-être appréhendée de manière globale entre Guadeloupe et Martinique, si on considère les contraintes biophysiques et économiques de la production et la structure de filière.
En première approche le choix de la banane en Guadeloupe comme support pour tester notre méthode a été motivé par plusieurs raisons :

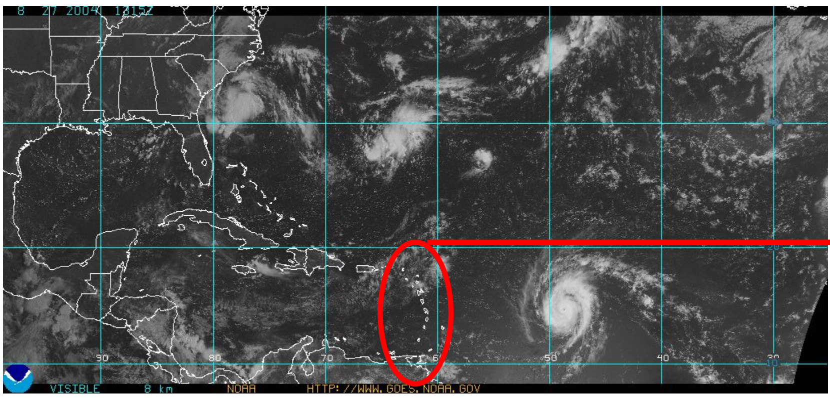
- les problèmes de durabilité sont multiples et sévères, et les attentes locales fortes : la banane antillaise est en proie à une crise économique, sociale et environnementale,

- la recherche agronomique locale (CIRAD et INRA) dispose d’un bon capital de connaissances sur le fonctionnement de l’agrosystème bananier et plusieurs innovations sont en cours de développement, ce qui rend l’exercice de l’application de notre méthode d’évaluation *ex ante* d’autant plus facile et pertinent,
- Il existe en Guadeloupe une grande diversité de contextes pédoclimatiques, techniques et économiques au niveau des exploitations, ce qui permet d’éprouver la robustesse et la praticité de la méthode.

Nous présentons ci-dessous les principaux éléments de la culture de la banane en Guadeloupe et des enjeux socio-économiques associés.

1.4.1. Géographie et milieu physique de la Guadeloupe

L’archipel Guadeloupéen est situé au milieu de l’arc insulaire des petites Antilles par 16° de latitude nord et 61° de latitude ouest (**figure 3**). Il est formé de 8 îles habitées et est fortement peuplé (227 habitants/km2). Les deux îles principales, la Basse-Terre et la Grande-Terre sont reliées par un étroit bras de mer, la Rivière Salée. La Basse-Terre est une île volcanique montagneuse de 848 km2 culminant à 1467m.



Source : National Huricane Center

Source : Atlas Bordas

Figure 3 : localisation de l’arc antillais et de la Guadeloupe

La température moyenne annuelle est de 24 à 26°C au niveau de la mer, et évolue selon un gradient altitudinal décroissant d'entre 2/3 et 3/4 °C / 100m, avec un faible contraste nycthéméral et saisonnier (moins de 8 degrés).
La Guadeloupe possède de nombreux écosystèmes naturels fragiles comme les barrières de coraux, lagons, mangroves, rivières, forêt primaire. La réserve du grand cul de sac marin a été classée réserve mondiale de la biosphère par l'UNESCO.

L'archipel s'interpose dans les alizés, vents toujours humides circulant d'est en ouest avec deux conséquences :

- La répartition spatiale de la pluviométrie est sous la dépendance de l'effet orographique et de l'effet de fœhn : élevée sur les versants est, de 2 à plus de 10 m/an lorsqu'on s'élève et que les masses d'air humide se refroidissent, elle décroît rapidement lorsqu'on redescend sur les versant ouest, pour atteindre la pluviométrie ordinaire sur l'océan, d'environ 1 m en année moyenne. La **figure 4** illustre le phénomène pluviométrique: la pluviométrie augmente avec l'altitude, et à altitudes égales, le versant exposé au vent (côte au vent) est plus arrosé que le versant sous le vent (côte sous le vent). Il existe une saison humide de plusieurs mois, au cours desquels le bilan hydrique est excédentaire, et où apparaissent un drainage et/ou un ruissellement importants, auxquels sont associés des risques d'érosion.

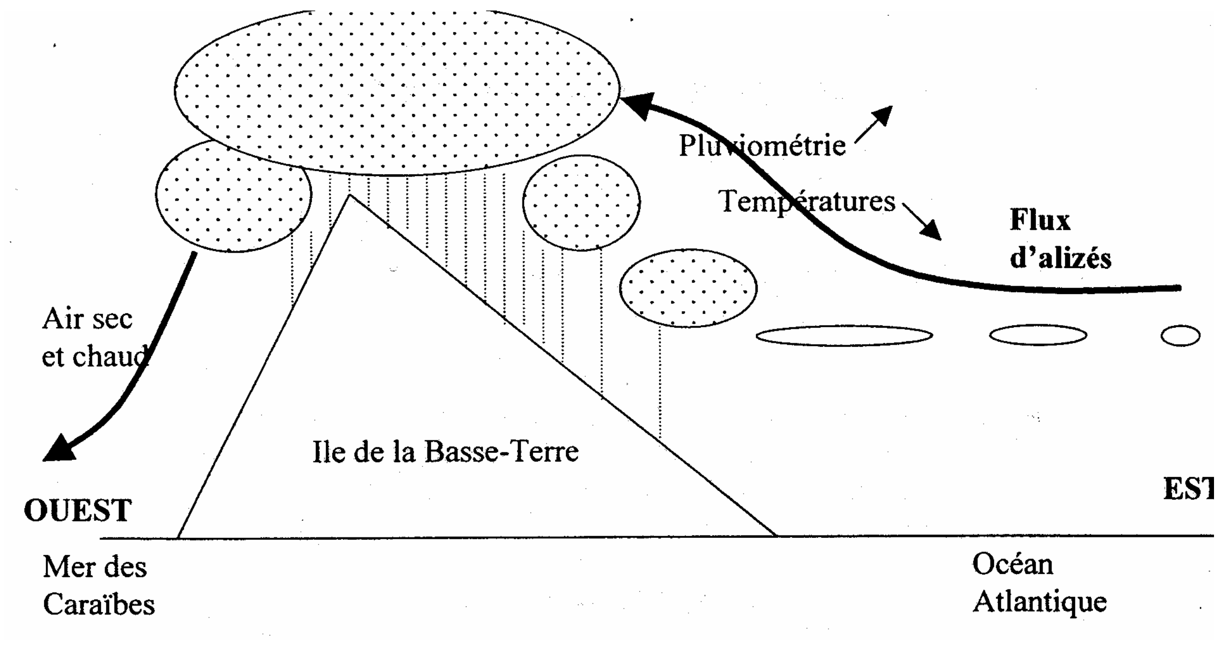
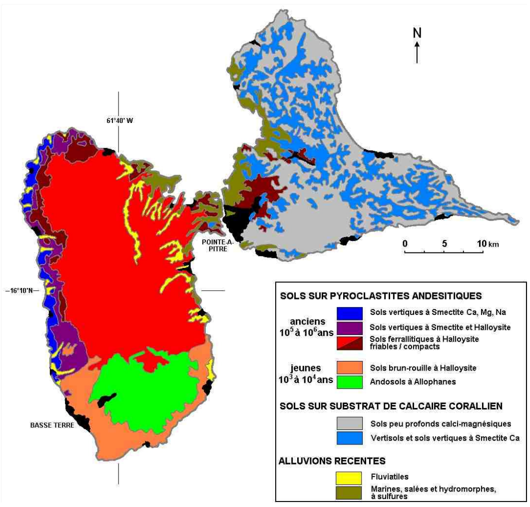


Figure 4 : L'effet de l'altitude sur la pluviométrie

- La Guadeloupe est exposée au risque cyclonique (tempêtes et ouragans tropicaux, voir cyclone Frances sur la photo satellite de la figure 3), avec des vents destructeurs des cultures, associés souvent (mais pas toujours) à des pluies de forte durée et intensité. Bien souvent, à la suite d'un cyclone, les planteurs sont obligés de replanter ou cycloner (pratique d'une section franche à la base du pseudo-tronc) la totalité de leurs parcelles en banane.

Les propriétés des sols, étagés dans le paysage, varient sur de courtes distances (**figure 5**). Plus la pluviométrie est élevée, plus la silice et les bases sont évacuées lors de l'altération, et plus les « argiles » qui se forment sont pauvres en silice et plus les sols sont acides. C'est ainsi que l'on trouve en Guadeloupe des sols riches en minéraux secondaires, de propriétés très différentes selon leurs natures, sous la dépendance de la pluviométrie et de l'âge des sols. Les andosols et sols bruns sont légers et bien adaptés à la culture de la banane (Dorel, 2001).



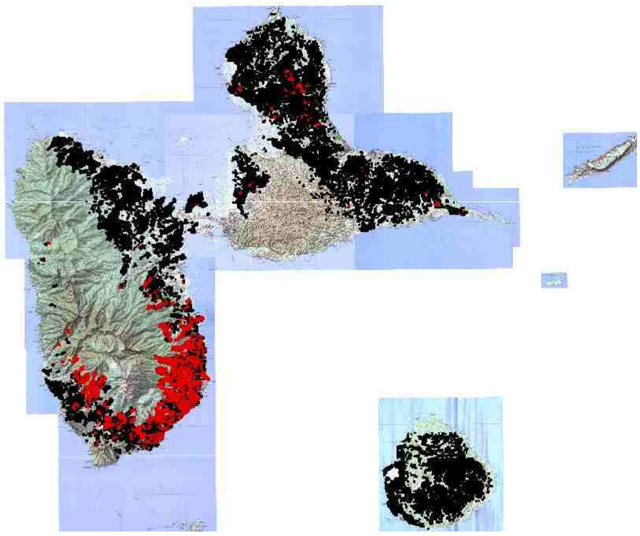


Figure 5 : carte des sols de la Guadeloupe
(Source : Cabidoche, communication personnelle)

Figure 6 : la sole bananière de Guadeloupe
(en rouge)

1.4.2. La culture de la banane en Guadeloupe

- **Localisation géographique :**

La culture de la banane se situe à 95% sur l'île de la Basse-Terre, sur les flancs de la Soufrière entre 0 et 800 mètres d'altitude. On dit qu'elle est concentrée dans la zone dite du « croissant bananier » comprise entre les communes de Petit-Bourg et de Vieux-Habitants (voir **figure 6**).

- **Aspects historiques**

La production de banane aux Antilles françaises s'est développée sous la colonisation suite au cyclone de 1928 qui a ravagé toutes les plantations de caféiers. La mise en place de mesures protectionnistes pour la banane française et la deuxième guerre mondiale ont contribué au développement de cette culture (approvisionnement de la métropole) dans un premier temps. Puis après la guerre et la départementalisation, la crise sucrière qui a entraîné la fermeture de toutes les usines (car pas assez compétitives sur le marché mondial) a définitivement entériné le succès de la banane en Basse-Terre où elle représente aujourd'hui avec 3000 ha et 220 planteurs près de 40% de la SAU. La Martinique comporte elle aux alentours de 580 planteurs pour une surface avoisinant les 7500 ha (IDEDOM, 2007).

- **Aspects macro-économiques**

La production de banane antillaise est destinée à 98% à l'export, elle est donc tributaire des cours mondiaux et des exigences standard de qualité qui portent sur le cultivar (Cavendish) et des critères de tri de la banane sur la base de considérations esthétiques de courbure, longueur et « griffures » des bananes. La production antillaise n'est qu'une très faible part de la production mondiale de banane pour l'export (environ 350 000 tonnes sur un total de 9.5 millions de tonnes, soit environ 4%), actuellement localisée en Amérique Latine (80% de l'export, principalement en Equateur, Colombie et Costa Rica), en Asie, et en Afrique. Sur les marchés extérieurs, la banane Antillaise est donc exposée à une concurrence des bananes « dollars » d'amérique et des bananes d'Afrique-Caraïbes-Pacifique (ACP) qui tend à se renforcer avec l'ouverture totale du marché communautaire intervenue au 1er janvier 2006, suite à la réforme du volet externe de l'Organisation Commune de Marché (OCM) de la banane. Compte tenu des écarts de compétitivité entre les producteurs-exportateurs et de l'importance de la filière dans l'équilibre socio-économique des Antilles françaises, l'Union européenne assure un revenu garanti aux producteurs dans le cadre du volet interne de l'OCM

banane, mais qui fait l'objet de réformes récurrentes. En 2008, les barrières douanières sont toujours présentes mais sous la pression de l'OMC elles devront être diminuées régulièrement de 170€/tonne à 110€/tonne d'ici 2016. La production Antillaise est soutenue par une aide compensatoire à hauteur de 400€/tonne sous réserve de l'atteinte d'un quota de production.
La banane est le fruit le plus consommé dans le monde avec une production globale (export et auto-consommation) estimée à 80 millions de tonnes par an. Les bananes sont une culture vivrière cruciale dans les régions tropicales puisqu'elles peuvent représenter jusqu'à 30% de l'apport calorique journalier, en particuliers en Afrique.

- **Aspects biologiques et techniques**

Le bananier : c'est une plante monocotylédone vivace de la famille des *Musaceae*. Les bananiers ont un mode de reproduction asexué qui procède par rejet végétatif à partir d'une pousse affleurant à la surface du sol (cf. **figure 7**). Les pousses ont une croissance vigoureuse, et peuvent produire un régime prêt à la récolte en une durée allant de 7 à 14 mois. Les rejets émergent régulièrement du bulbe racinaire, faisant par là du bananier une culture pérenne.

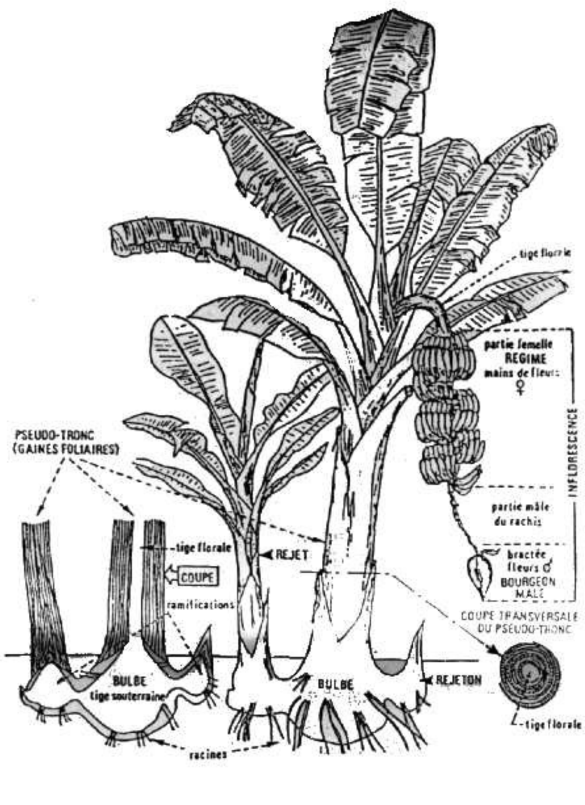


Figure 7 : Vue schématique d'un bananier à sa fructification
et de ses rejets (Source : Fruits, numéro spécial « La banane »).

Plantation : elle intervient lorsque l'on est en situation semi-pérenne, tous les 4 à 6 ans, certaines bananeraies n'étant elles jamais replantées. On replante alors, avec ou sans travail du sol mécanisé, soit des rejets issus d'autres parcelles, soit des vitro-plants qui ont l'avantage d'être exempt de nématodes, et sont préconisés après une jachère.

Apports d'intrants : classiquement les agriculteurs font des apports d'engrais de fond annuellement (chaux), et des apports réguliers en engrais ternaire NPK (tous les mois au mieux). Les planteurs ont aussi recours à des pesticides du type herbicide, insecticide pour contrôler le charançon du bananier *Cosmopolites sordidus*, nématicides pour contrôler le nématode endophytoparasite *Radopholus similis*, principal ravageur de la culture, et des fongicides pour lutter contre la cercosporiose qui provoque un jaunissement des feuilles causé par les champignons *Mycosphaerella musicola* et *Mycosphaerella fijiensis*.

Soins au bananier :

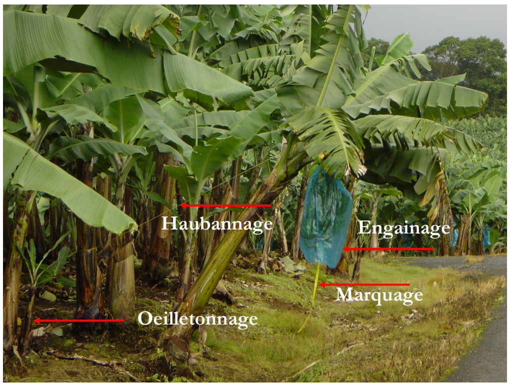
- oeilletonnage qui consiste à sélectionner le rejet qui assurera la production du cycle suivant (environ 3 ou 4 fois par an)
- effeuillage qui consiste à supprimer régulièrement (environ tous les 15 jours) les feuilles sénescentes ou attaqués par des maladies,
- haubanage qui consiste à attacher les bananiers avec une ficelle afin d'éviter sa chute ou la casse du pseudo-tronc,

Soins au régime :

- dégagement : coupe de toutes les feuilles qui touchent le régime, et ablation des fausses mains (les dernières mains du régime),
- marquage chaque semaine des régimes au stade floraison par une bandelette de couleur en vue d'en prévoir la date de récolte optimale à partir d'une somme de degré jours,
- engainage qui consiste à mettre une gaine plastique autour du régime en vue d'en améliorer la qualité et pour le protéger contre certains insectes ravageurs (Thrips en particulier).

Récolte et emballage : elle intervient au plus toutes les 2 semaines et elle est réalisée à l'échelle de l'exploitation. Une récolte de tous les régimes mûrs est effectuée (régime mûr = une certaine couleur de bandelette de marquage), ceux-ci sont alors transportés au hangar de l'exploitation avec une remorque. Au hangar, les régimes sont pendus, dépattés, trempés dans un bain (précipitation du latex et traitement contre l'antrachnose), les bananes sont ensuite triées selon les standard de qualité, puis empaquetés dans des cartons de 18.5 kg de banane.

Les opérations au champ



Les opérations de conditionnement de la banane au hangar

Les cartons peuvent alors être palettisés et mis en conteneur, ou si le planteur n'a pas la capacité de remplir seul un conteneur, directement transportés au centre d'empotage avec une camionnette où les cartons seront mis dans des conteneurs commun. Les opérations de récolte et emballage représente de 30 à 50% du besoin en travail total.

La culture de la banane est caractérisée par son exigence en main d'œuvre (environ 0.6 UTA/ha) due à la présence de nombreuses opérations manuelles qui ne peuvent être mécanisées. Aux Antilles les exploitations bananières sont très souvent entièrement spécialisées dans la banane.

1.4.3. Enjeux socio-économiques et environnementaux des systèmes de culture bananiers

La culture de la banane est d'une importance économique et sociale considérable aux Antilles. Dans un contexte où le taux de chômage est de l'ordre de 25%, cette culture représente environ 5000 emplois directs ou indirects. Par ailleurs alors que la balance commerciale de la Guadeloupe est largement déficitaire (taux de couverture de 7%), l'exportation de banane représentait en 2006 40 millions d'euros sur les 164 millions d'euros de la totalité des exportations de marchandises (INSEE, 2007). En ce qui concerne la Martinique la dépendance à la banane est encore plus marquée.
Cependant cette culture traverse une crise économique et environnementale sévère depuis le début des années 90. La crise économique est due d'une part à la libéralisation du marché qui a entraîné une baisse du prix de vente sur le marché mondial, et d'autre part à la faible compétitivité de la production antillaise face aux pays producteurs d'Amérique latine et d'Afrique où les coûts de main d'œuvre sont de 5 à 10 fois plus bas, et les structures d'exploitation beaucoup plus grandes (surface médiane de 4 ha aux Antilles). Parallèlement à la baisse du prix de vente, les coûts de production ont augmenté avec la systématisation de l'usage du labour en zone mécanisable et de pesticides coûteux pour contrôler le développement parasitaire en charançons et en nématodes. Par ailleurs, les Antilles ont été touchés par de nombreux cyclones destructeurs avec Hugo en 1989, Luis et Marylin en 1995, Lenny en 1999 et Dean en 2007. La grève des dockers du port de Pointe à Pitre en 2004 qui a empêché toutes exportations pendant 2 mois a également contribué à fragiliser des exploitations déjà déprimées économiquement. Cette crise économique s'est traduite par une

érosion du revenu (Bonin and Cattan, 2006), un manque de trésorerie chronique pour financer la production (Dulcire and Cattan, 2002; Cattan and Dulcire, 2003), et une chute vertigineuse du nombre d'exploitations.

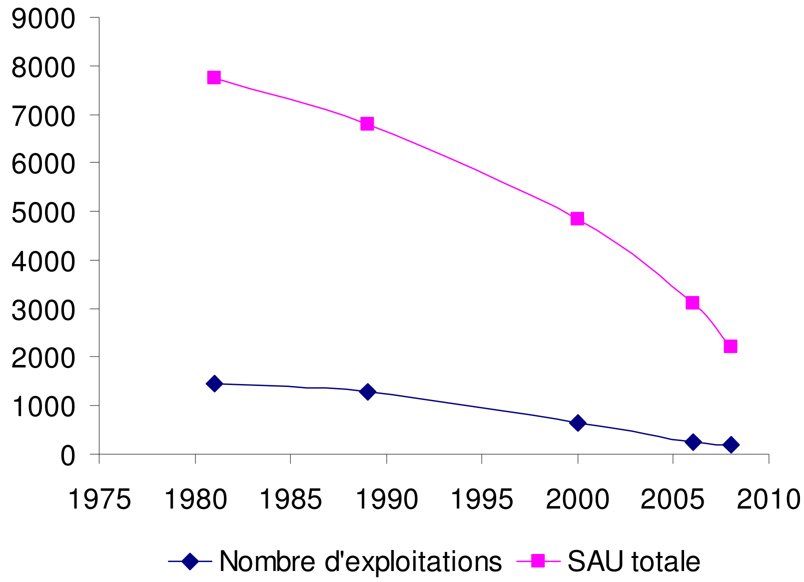


Figure 8. Evolution du nombre d'exploitants et de la SAU totale (en hectares) concernée par la production de banane (Source données: OP « *Les producteurs de Guadeloupe* », communication personnelle)

Les pratiques intensives ont eu pour conséquence une baisse de la fertilité physique, biologique et chimique des sols (Clermont Dauphin et al., 2004) et une contamination des sols, des eaux de surface, et des écosystèmes terrestres et marins en composés organochlorés et organophosphorés (Bonan and Prime., 2001; Bocquene et al., 2005, Houdart et al., 2008).

En 2000 a éclaté une affaire de pollution de captages d'eau potable à la chlordécone (une molécule pesticide autrefois utilisé pour lutter contre le charançon) qui a été très médiatisée et a débouché sur l'installation systématique de filtres à charbon actif sur grain dans tous les captages. Depuis la pollution à la chlordécone occupe régulièrement la une des médias locaux tant en Guadeloupe qu'en Martinique. La pollution des sols en cette molécule est durable puisque de récentes études ont montré que les sols seraient pollués pendant plusieurs siècles (Cabidoche, *in press*). Les populations locales sont inquiètes car certaines productions (en particuliers les tubercules) peuvent être contaminés si ils ont été produits sur des sols fortement pollués. Ceci a amené les pouvoirs publics à prendre des mesures (décrêts préfectoraux) obligeant l'analyse des productions issues des sols contaminés préalablement à

la commercialisation (DAF, 2003; 2005). Ainsi les possibilités de diversification sont très restreintes pour les exploitations bananières.
Couplée à la forte pression médiatique et sociale et à la crise économique, cette situation amène donc les systèmes de cultures bananiers à devoir évoluer vers des systèmes à moindres niveaux d'utilisations de pesticides et plus performants économiquement.

1.4.4. Vers de nouveaux systèmes de culture

Témoin de la volonté des planteurs d'innover, les groupements de producteurs Antillais sont en train de négocier en appui avec le ministère de l'agriculture le financement d'un plan d'amélioration de la durabilité de la production de banane par la communauté européenne, le « plan banane durable ». Ce plan porterait sur le développement d'innovations agro-écologiques en coordination avec la recherche, l'amélioration de l'appui technique aux planteurs avec la création d'un institut de la banane, et le développement d'une politique marketing autour de la durabilité de la banane antillaise.
En ce qui concerne les innovations technologiques, la recherche agronomique locale travaille depuis une quinzaine d'année sur différents éléments d'innovation en vue du développement de systèmes de cultures innovants. Au début des années 90 apparaissent ainsi les vitro-plants, qui sont des plantules de bananier produites *in vitro* à partir de cultures méristématiques et donc exemptes de nématodes. Cette innovation à l'avantage d'éviter la contamination de la parcelle à la plantation, ce qui peut être le cas si la plantation est réalisée avec des rejets prélevés sur des parcelles infestées. Cette innovation coûteuse (1€ par vitroplant, subventions déduites, avec environ 1850 plants/hectare) n'est cependant efficace que si la plantation est précédée d'une jachère assainissante. Des recherches complémentaires ont montré que le rôle du mode de destruction de la parcelle de bananier avant mise en jachère était crucial pour que la jachère soit efficace (Chabrier et Quenehervé, 2003). Malgré le fait que cette innovation permette de considérablement réduire l'usage de nématicides et/ou d'augmenter le rendement, son adoption reste faible en général, en particuliers au niveau des petites exploitations (Bonin et Cattan, 2006). D'autres innovations sont en cours de développement, comme les « plantes de service » (plantes cultivées en association à la banane qui pourraient fournir divers services de facilitation de la nutrition azotée du bananier, la maîtrise des mauvaises herbes, la réduction de l'érosion, etc.) et de nouveaux hybrides de bananiers tolérants aux maladies fongiques et aux nématodes qui possèdent de nouvelles caractéristiques commerciales (taille plus petite, goût différent, etc.).

Du point de vue de la dynamique d'innovation qui est en cours aux Antilles, les objectifs finalisés de notre travail seront de (i) dresser un état des lieux et caractériser la diversité des situations existantes (chapitre 2), (ii) mettre en cohérence les éléments d'innovations en cours de développement pour en faire des systèmes de cultures innovants *a priori* adaptés aux problèmes et contraintes des planteurs (chapitre 2), (iii) évaluer *ex ante* et à l'échelle des exploitations quels seraient les impacts économiques, techniques, agronomiques, environnementaux de l'adoption des systèmes innovants (chapitres 3 et 4), (iv) évaluer quelles sont les probabilités et conditions d'adoption des systèmes par les planteurs (chapitre 5), et (v) formuler des propositions d'action à destination des agronomes concepteurs, économistes de l'innovation, et acteurs et décideurs de la filière (DAF, ministère de l'agriculture, groupements de planteurs) en vue d'éclairer leur choix dans le développement et l'adoption de systèmes plus durables (chapitre 6).

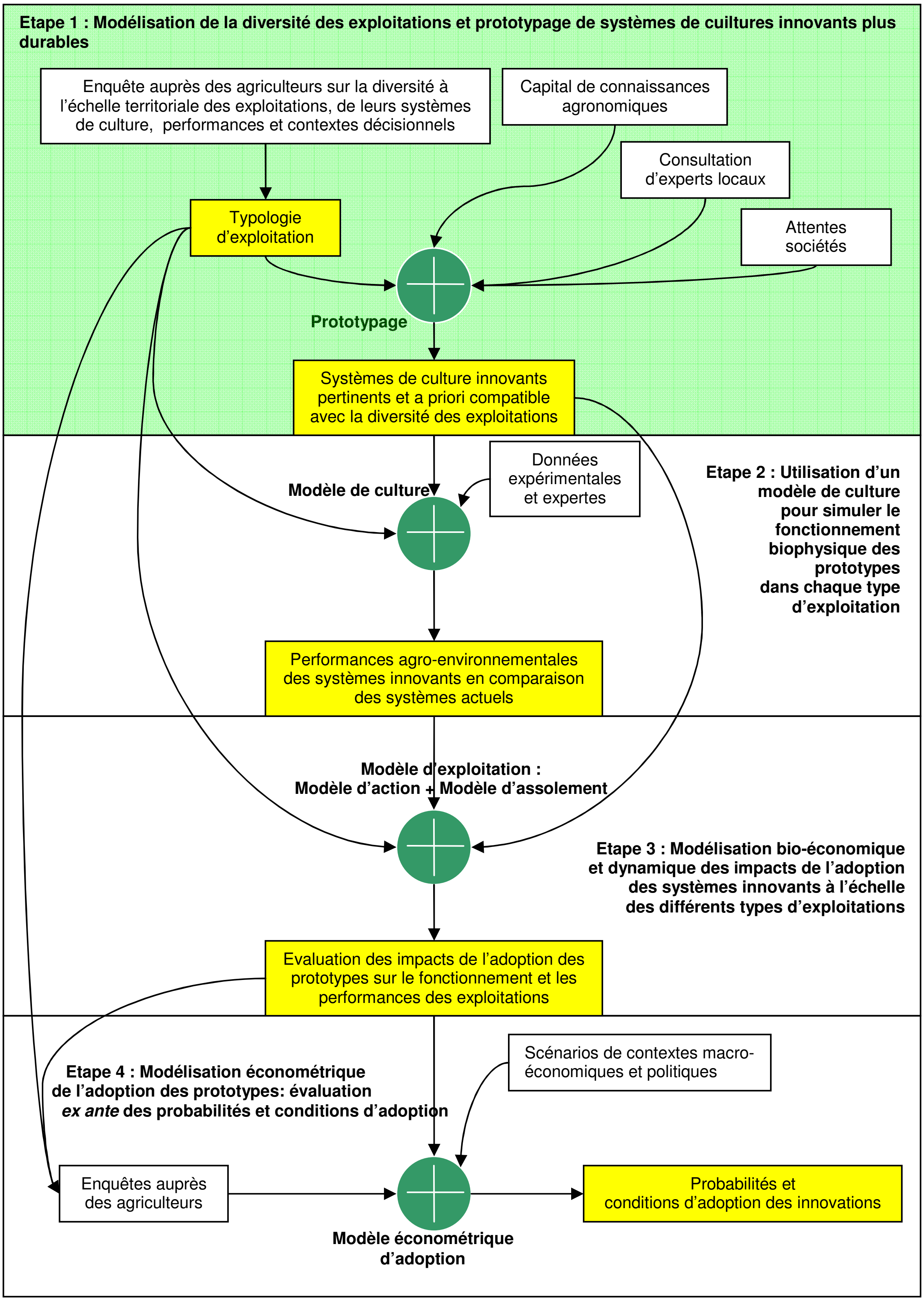


Figure A : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

2. Modélisation de la diversité des exploitations et prototypage de systèmes de culture innovants plus durables

Ce chapitre correspond à la description de la première étape de la méthode (cf. figure A).

Cette étape à deux objectifs au sein de la démarche globale:

- Construire une typologie d'exploitation pour modéliser la diversité des exploitations à l'échelle régionale en terme de système de culture pratiqué, contexte biophysique et socio-économique, et de performances.

- Mener une action de prototypage de systèmes de culture innovants impliquant le croisement de la typologie avec des savoirs experts, des connaissances agronomiques (bibliographie), et les attentes de la société.

La méthode proposée pour conduire cette première étape ainsi que les résultats de son application aux systèmes de culture bananiers de Guadeloupe sont présentés dans l'article suivant, intitulé **« A methodological framework for taking into account the diversity of farms in the prototyping of sustainable crop management systems. Application to banana-based systems in Guadeloupe »**, qui a été soumis à la revue ***Agricultural Systems*** (http://ees.elsevier.com/agsy/).

Par souci de commodité, les références de l'article ont été mises à la fin de ce document, avec les références de la globalité de la thèse.

A methodological framework for taking into account the diversity of farms in the prototyping of sustainable crop management systems. Application to banana-based systems in Guadeloupe.

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Abstract

Prototyping methods are operational for designing alternative sustainable crop management system (CMS) but are considered mainly at field level with a poor coverage of farm diversity in terms of economic, social or natural constraints. This could limit the likelihood of adoption of alternative CMSs. The objective of this paper is to propose a two-parts methodological framework allowing for such an accountment. Using the concept of crop management system context (CMSC), which we propose to define as a set of characteristics at farm level likely to influence the structure and the biophysical and economic performance of CMS at field level, the first part of the framework consists of the design of a farm typology able to characterize the diversity of current CMS, constraints context (CMSC), and CMS performance (CMSP). The typology is designed from a statistical analysis on a set of descriptive variables collected through a farm survey on a sample of farms. The second part of the framework uses this farm typology in a specific work agenda with a panel of experts involving five steps : i) defining the main objectives of the CMS prototypes on the basis of a performance analysis of current CMSs, ii) identifying suitable biotechnical functions to reach these objectives, iii) identifying crop management techniques to be further combined in CMS able to mobilize these functions, iv) defining the context of constraints in which the CMS will be applied and assessed (CMSC), v) identifying a variety of CMS prototypes able to mobilize the functions and compatible with the different CMSCs, using the confrontation of the prototypes with the CMSCs through a global compatibility indicator. We propose to define a prototype as compatible with a CMSC provided it does not increase the expression of sensitive constraints at farm level. The method has been tested on the example of banana-based cropping systems in Guadeloupe. It showed the existence of a great diversity of CMSs responsible for different performances (CMSP) and corresponding to different economic, environmental and social CMSCs (6 farm types). The method led to the prototyping of 16 innovative CMS, involving different modalities of intercropping, regulation of pesticides use, hybrid cultivars, and rotations with cover or cash crop. The paper finally discusses the genericity and limits of the methodological framework and how it could be useful to combine it with an experimental or model-based assessment of innovations on the different farm types.

Keywords: prototyping; crop management system; farm typology; low input innovation, Guadeloupe; Musa spp.

2.1. Introduction

In most developed or developing countries cropping systems have to face severe changes like climate change, market liberalization and emergence of new environmental or economic constraints. Subsequently, farmers have to adapt rapidly their crop management systems to these new constraints. This has led research on farming and cropping systems to show a growing interest in the development of methodologies to design and evaluate multi-objective innovative crop management systems (CMS) .

According to the classification of Sterk *et al.* (2007) the main tools developped for prototyping innovative CMS can be classified into three categories: (1) computer modelling; (2) cropping system experiments at experimental stations; (3) on-farm research or action research on pilot farms. Model-based prototyping makes it possible to rapidly evaluate a large number of CMSs with a wide range of conditions (Tixier et al., 2008; Loyce et al., 2002, Dogliotti *et al.*, 2003, 2004), but the range of cropping techniques and of assessement criteria is limited by the capability of the model (Lancon et al., 2007). Experiment-based prototyping approaches can produce innovative cropping systems combining a large set of techniques in an integrated crop management system but are limited by a very specific adaptation to soil-climate-farming conditions for which they have been designed (Lançon *et al.*, 2007). One of the well-documented examples of the methodology of prototyping is the "in farm prototyping" method that has been developed by Vereijken (1997). It consists of translating a set of ranked agro-ecological or economic goals into theoretical prototypes with the involvement of scientific or agricultural expert knowledge. The prototypes are then implemented on pilot farms (experimental or commercial) and the method consists of assessing the capacity of the prototypes to fulfil the objectives, and improving their design iteratively. This method of on-farm prototyping has been used both in developed and developing countries and is considered as operational (Stoorvogel, 2004).

Several shortcomings of prototyping approaches can be identified. First there is rarely mention in the examples of prototyping approaches of how objectives and constraints for innovations to be designed were chosen and how alternative management options were identified from these objectives and constraints (Sterk *et al.*, 2007). Moreover, published approaches consider one or few theoretical, typical or average situations which can be far from reality, seldom accurately described, and thus do not take into account the diversity of farming situations to which the innovations are applied (Sterk *et al.*, 2007). Experts are often mobilized in prototyping approaches but the way they are involved is seldom formalised and they pay little attention to farm diversity.

However, some innovative CMSs might be very efficient in some farming contexts and completely inadequate in others (Orr and Ritchie, 2004), mostly because of specific environmental, economic and technical contexts, which vary widely among farmers (Bernet *et al.*, 2001). Furthermore innovation adoption is a complex process that depends on many determinants relative to farmers' socio-economic and personal characteristics, as well as on the attributes of the innovations (Feder and Umali, 1993; Abadi Ghadim and Pannell, 1999; Marra *et al.*, 2003; Edwards-Jones, 2006). As a consequence the design of relevant prototypes of crop management systems in a territory should be based on the characterization of the diversity of current CMSs and of the biophysical and economic context which can influence their structure and their economic and biophysical performances. These farm characteristics thereby define a 'crop management system context' (CMSC), whose diversity has to be assessed and be taken into account as specific sets of constraints. This will ensure a better matching of the innovative CMS prototypes with the CMSC of each farm type and thus improve their likelihood of adoption at regional level. There is a need to assess whether a crop management technique is compatible with a CMSC, i.e. whether it can be incorporated in a CMS without increasing the expression of the main constraints at farm level.

The objective of this paper is to present a two-part transparent and formalised methodological framework that makes it possible to take into account farm diversity in the prototyping of innovations. The first part of the framework consists in assessing the diversity of CMSs in terms of technical nature, performance and main socio-economic and biophysical constraints. The second part is the step by step involvement of experts to identify relevant prototypes of innovative CMSs compatible with the different farming situations.

This paper first presents the framework we proposed and then the results obtained with its application to the design of an innovative technical management system for bananas in Guadeloupe, French West Indies.

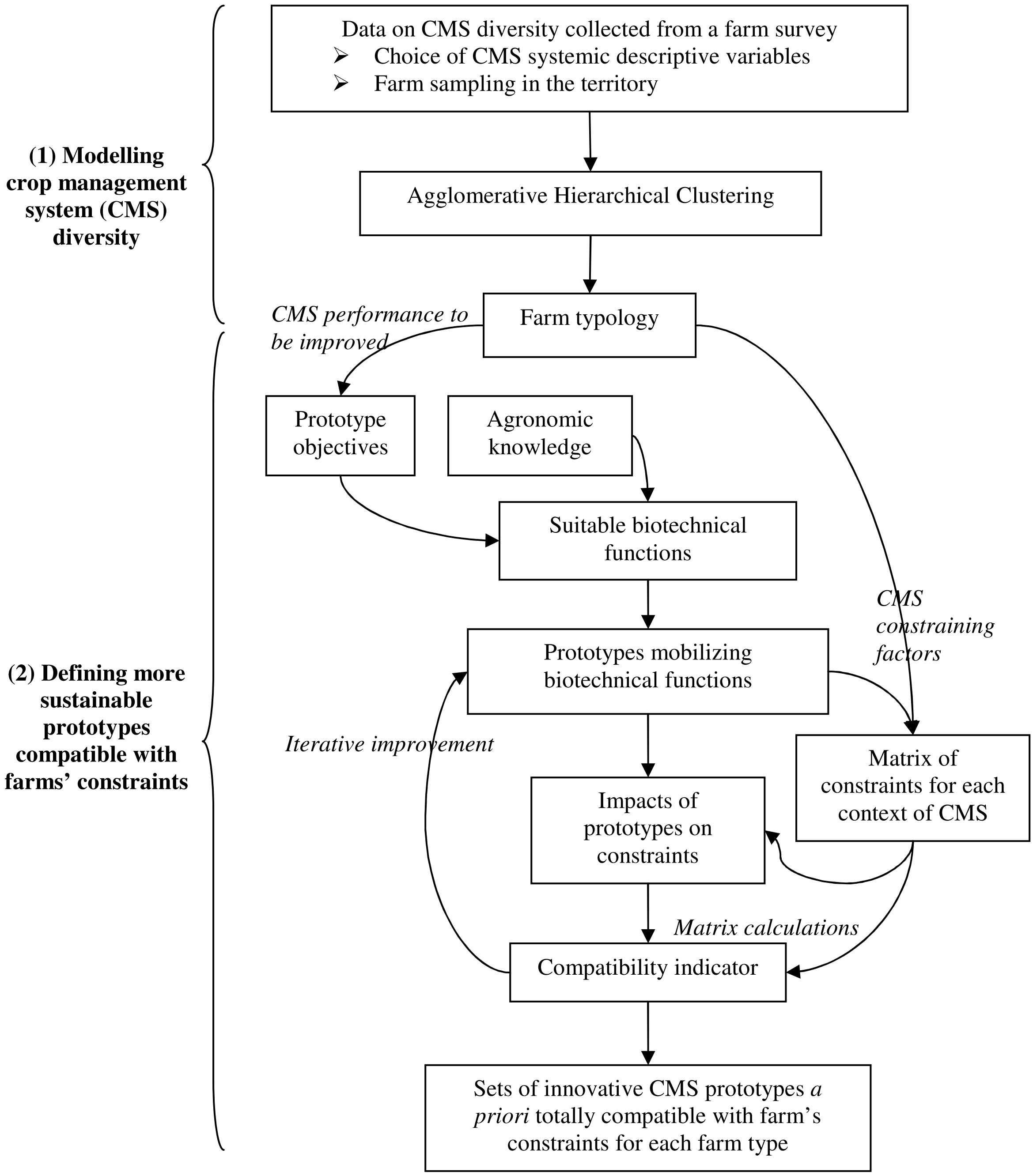

Figure 1. The different steps of the method and their outputs.

CMS = Crop Management System (Rapidel et al., 2006)

2.2. The proposed methodological framework

2.2.1. Overview

Figure 1 gives a simplified overview of the two-step framework. The second step represents the prototyping process *stricto sensu,* and is largely based on the outputs of the first step. The key component of the first step is the design of a farm typology able to modelize farm diversity in the region. This diversity is relative to the CMS to be improved, to its performance (CMSP), and to the constraints in its decisional context at farm level (CMSC). This representation allows a systemic and functional characterization of CMS. The typology is built through a statistical treatment involving Agglomerative Hierarchical Clustering (AHC) from a set of descriptive CMS, CMSP and CMSC variables collected through a survey on a sample of farms. This farm sample has to provide a representative overview of the regional diversity of CMS. The farm typology is then an input of the second step involving a series of meetings with experts from different agro-ecological disciplines, which aim at designing relevant prototypes compatible with the different farming situations (i.e. CMSCs) at territory level. We considered that a prototype is relevent when it makes possible the improvement of performances of a CMS, and is totally compatible with a farm type provided it does not increase the expression of sensitive constraints at farm level. The schedule for this second step is as follows : i) defining relevant objectives for innovations to design according to current CMSP, ii) identifying suitable biotechnical functions to reach these objectives, iii) identifying a variety of prototypes able to mobilize the biotechnical functions, iv) defining specific sets of constraints for each farm type (CMSC) that could render the prototypes impractical, iv) analysing the global compatibility of each prototype with each farm type through a compatibility indicator, and v) a process of iterative improvement of protototype design until identifying one or several prototypes *a priori* totally compatible for each farm type.

2.2.2. Step 1: designing a farm typology

The objective of the typology is to model the diversity of CMS, CMSC and CMSP at regional level. It is based on interviews with a sample of farmers, and the use of a statistical process of hierarchical grouping.

Questionnaire design and sampling

To prototype innovative CMS we do not have to focus on a specific component of current CMS (for example "sowing or plantation date" or "irrigation planning") because we don't know *a priori* the innovations that should be integrated in the CMS and the components to be modified. The CMS has indeed to be described as a whole with a set of decision rules covering all operations. Farmer's decisions are interdependent because they are influenced by a number of specific objectives and constraints at a strategic level of the farming system (Meynard *et al.*, 2001; Osty *et al.*, 1998; Sebillote and Soler, 1990). The objective of the survey is to collect a set of variables that would make it possible to understand these interrelationships. Therefore, in order to identify these interrelationships, we need to place the CMS within a systemic description (Rapidel et al., 2006) relative to i) its technical nature, in terms of sequency and modalities of operations on the crop (the CMS itself); ii) its economic, social and physical context (CMSC) that are likely to influence its nature and performance; and iii) its agronomic, environmental and socio-economic performance (CMSP). CMSPs define the assessment criteria of the CMSs in the specific context of each farm type (CMSC).

The number of variables to collect for these three categories (CMS, CMSP and CMSC) should be of the same order of magnitude, in order not to bias the typology. In particular too many economic variables should be avoided because they are frequently correlated. Concerning the choice of the CMSC variables, certain variables are needed whatever the situation and the region in which the method is implemented, because they are systematically highlighted in extensive and numerous studies and reviews as having a key influence on the farmers' decision making process : resource endowments, labor availability and nature, financial and credit constraint, socio-economic status, demographic characteristics, and access to institutional services such as extension, input supply, markets (see Feder and Umali, 1993; Feder *et al.*,1985; Edwards-Jones, 2006).

CMSs should be extensively described, because for a given crop, different CMSs can be found on the same farm. However, to simplify the analysis and limit the number of variables we suggest considering for each farmer only one CMS, representative of most of the fields.

To provide a good representation of the technical, economic, social, soil and climatic diversity, farm sampling should first include a preliminary stratification of the population according to certain factors assumed to account for total variability. We consider as a minimum a sampling rate of 10% of the total population of farms.

Statistical analysis

To construct homogenous groups of farms from the data, we use a two-step statistical treatment. The first step is to transform the quantitative variables into quantitative non-correlated variables with a Principal Component Analysis (PCA). The advantage of this preliminary treatment is that it enables filtering out of statistical noise from the data by taking into account only the first components of the PCA. If the questionnaire includes more qualitative than quantitative variables, a multiple correspondence analysis (MCA) can be used. Individuals are then grouped into specific farm types with an algorithm of Agglomerative Hierarchical Clustering (AHC) using as input variables the principal components of the PCA (or of the MCA). This method has been used in many studies to categorize farms or farmers' practices (Bellon *et al.*, 2001; Maseda *et al.*, 2004). In the AHC, a weighting of these variables according to the corresponding eigenvalues can be done to take into account the level of variance explained by each one (this option is not possible with a preliminary MCA as interpretation of total variance has no statistical significance in this case). The AHC consists of progressively grouping individuals according to their resemblance, measured through an index of dissimilarity. A simple and useful index can be the Euclidian distance (D) expressing the distance between individual **a** and individual **b** described by **i** variables **x** by:

$$\mathbf{D(a,b)=[\Sigma_i(x_{i,a}-x_{i,b})^2]^{0.5}}$$

The use of the euclidian distance as a dissimilarity index is useful as it makes it possible to take into account different multidimensional normalised variables in a single criteria. The algorithm then groups individuals into pairs by selecting the individuals whose distance D is a minimum at each step. The pairs thus obtained are then aggregated with Ward's minimum-variance method. It consists of progressively aggregating individuals by minimizing the augmentation of the total intra-class inertia. The advantage of this method is that it allows for very homogenous classes to be obtained. The characterization of the farm types can be made by selecting the mean or modal value of each variable in each group of farms, respectively for the quantitative one and the qualitative one. For testing which variables are significantly correlated with type membership, we uses calculations of coefficient of variations and analysis of variance for quantitative variables and percentage of modal value and Khi² tests for qualitative ones.

2.2.3. Step 2: Prototyping innovative CMSs with experts

The approach

The objective of this step is to propose a set of innovative CMS prototypes, by modifying some decision rules in the current CMS or introducing new cropping techniques. The method for designing such innovative prototypes of CMS is based on the involvement of a panel of experts. This panel has to account as much as possible for all kinds of agro-ecological knowledge on the whole or on a part of the CMS to be improved, and should cover a good knowledge of the territory both at biophysical, economic and technical level. The method is based on a working agenda involving five steps that have to be covered during several meetings of the experts. The meetings are based on discussions facilitated by the person who leads the prototyping and are aimed at designing different tables and matrices at each step. As a general rule the experts are invited to confront their points of view until a general consensus on the tables and matrix is reached, but without limiting the number of outputs. The objectives and the rules of the meetings and the typology obtained in step1 are presented to the experts during a first preliminary meeting.

Working agenda and compatibility indicator

i) The first step consists of defining objectives for the design of the prototypes according to CMSPs characterized in the typology. With the general aim of improving the sustainability of each farm type, this meeting consists of identifying critical performances relative to one specific component of sustainability (e.g. environmental) or to several components (e.g. economic, environmental and social) for each type.

ii) The aim of the second meeting is to identify suitable biological or technical functions to reach these objectives. These biotechnical functions are seen as ways of achieving the objectives defined in the substep one. Hypotheses relative to the effects of the biotechnical functions on the objectives have to be discussed in this step, and are largely based on a capital of agronomic knowledge. At the end of this meeting a table 'objectives * biotechnical functions' has to be obtained for the different farm types.

iii) The third meeting consists of identifying a variety of prototypes able to mobilize the biotechnical functions. A prototype is an adaptation of a current CMS and can integrate modifications of decision rules in crop management, modifications of the crop pattern, introduction of new technologies in the CMS. The identification of potential prototypes is made without limitations on the number of prototypes or the level of innovation in the CMSs.

This step is based on the experts' knowledge of the functioning of the cropping system and on how to improve it.

iv) The fourth meeting consists of designing a matrix of constraints defining the context of constraints into which the prototypes have to fit for each farm type (CMSC). This makes it possible to obtain a matrix '"constraints by farm type" describing the different CMSCs and to identify the critical constraints that would likely be increased in each farm type by the adoption of each prototype. This leads to the definition of a matrix that confronts all prototypes with all constraints in order to highlight which prototype is likely to increase which constraints. The nature, number and formulation of the constraints are chosen by the panel of experts.

v) The last meetings consists of assessing the level of compatibility of each prototype with each farm type through a 'compatibility indicator'. The aim of this indicator is to allow the identification of prototypes *a priori* totally compatible with all potential constraints for each farm type. The total compatibility indicator value $\mathbf{C_{x,y}}$ measuring the total compatibility between prototype **x** and farm type **y** for **z** constraints **w** is calculated with the following equation:

$$\mathbf{C_{x,y} = 1 - [\Sigma_{w=1:z}(I_{x,w} * T_{w,y}) / (\Sigma_{w=1:z} T_{w,y})]] \quad (1)}$$

with $\mathbf{I_{x,w}}$ = 1 if prototype **x** is likely to increase constraint **w**, 0 otherwise;

and $\mathbf{T_{w,y}}$ = 1 if constraints **w** is present in the CMSC of farm type **y**, 0 otherwise.

Expression (1) can be written in matrix form as:

$$\mathbf{C = 1 - [I * TR] \quad (2)}$$

with $\mathbf{C=(C_{x,y})}$, $\mathbf{I=(I_{x,w})}$ and $\mathbf{TR=(TR_{w,y})=(T_{w,y} / \Sigma_{w=1:z}T_{w,y})}$.

When the component $\mathbf{C_{x,y}}$ of matrix **C** is equal to 0, it is easy to see that prototype **x** is likely to increase all constraints present on the CMSCs of farm type **y.** When this indicator is equal to 1, prototype **x** is totally compatible with farm type **y** as it is likely to increase none of the constraints present in the CMSC of farm type **y**.

The use of the matrix **C** and of a process of iterative improvement of protototype design involving substep 3, 4 and 5 makes it possible to obtain for each farm type one or several prototypes *a priori* totally compatible, which marks the end of the meetings.

Category		Code	Definitions	Units
Banana Crop Management System (CMS)		DES	Dummy variable : Type of destruction of banana fields before replanting : mechanized, chemical, or manual	-
		PLO	Dummy variable : Type of ploughing : mechanized or manual	-
		ROT	Dummy variable : 1 if fallow or rotations present in banana annual rotation; otherwise 0	-
		ANE	Dummy variable : 1 if nematode monitoring through root analysis; otherwise 0	-
		REP	% of banana area replanted each year	%
		VPL	% of seedlings produced by tissue culture and nematode-free (vitro-plants)	%
		QFE	Amount of fertilisers applied per plant at one passage	g
		FFE	Number of applications of fertilisers each year	units
		HER	Number of herbicide treatments per year	units
		NEM	Number of nematicide treatments per year	units
		PRP	% of banana plants replaced each year	%
		FLO	Amount of annual post-flowering work to bunches for banana quality management	days ha-1yr-1
		ANC	% of flowered plant cabled for bunch weight support	%
		PAC	Number of harvest and packaging operations per year	units
Context of banana Crop Management System (CMSC)	economic resources	TEN	Dummy variable : 1 if total land tenancy; otherwise 0	-
		SUB	Dummy variable : 1 if farmer's land is fractioned ; otherwise 0	-
		EXI	Dummy variable : 1 if farmer has off-farm income 0 otherwise	-
		CAS	Dummy variable : 0 if the farmer is cash-flow limited; otherwise 1	-
		INV	Dummy variable : 1 if farmer has investment capacity; otherwise 0	-
		LAN	Total farm land area	ha
		IRR	% of SAU with access to irrigation	%
		NFA	Number of farms owned by the farmer	units
	farming system	MPC	Average daily cost of labour work on the farm	€ day-1
		BAN	% of SAU cultivated with banana	%
		DIV	% of agricultural income from crops other than banana	%
	physical context	SOI	Dummy variable : Type of soil : andisol, ferralitic, or nitisol	-
		ALT	Average altitude of the farm	m
		MEC	% of SAU suited for mechanical ploughing	%
		SLO	Average slope of the farm land plots	%
	personal ambition	PRO	Dummy variable : Farmer project for the strategic guidance of his farm : establishment, stabilization, diversification, or abandonment	-
	social	STU	Dummy variable : 0 if no training, 1 if agricultural training, 2 if higher studies	-
		INF	Dummy variable : 0 if no contact with extension agents, 1 if contact with extension agent, 2 if contact with local agricultural research centre	-
		AGE	Age of the farmer	year
		FAM	% of family workers	%
		TEM	% of total work by temporary workers	%
Perfomances of banana Crop Management System (PCMS)	agronomical	CYC	Cycle duration in months	month
		MAT	% of banana losses during export chain due to early maturation	%
		YIE	Average yield of banana fields	t ha-1 yr-1
		BUN	Weight of bunch indicator (average number of 18.5 kg boxes filled with one bunch)	boxes bunch-1
		REJ	percentage of rejected bananas	%
	economic	QUA	Quality : average return from bananas according to their quality	€ / kg-1
		EFP	Work efficiency of packaging chain expressed in boxes per workday	boxes day-1
		WOR	Annual work demand	days ha-1 yr -1
		PCO	Production costs	€ ha-1 y-1
		BNM	Banana net margin	€ ha-1 y-1
	environnemental	AMP	Amount of active matter of herbicides and nematicides applied each year	kg yr-1

Table 1. Definition of variables used for building a farm typology of banana growers in Guadeloupe.

2.2.4. Application of the method to Guadeloupean banana's CMS

Guadeloupean banana production for export is facing a severe economic and environmental crisis due to market liberalization and the emergence of new environmental constraints such as pesticide regulations (Dulcire and Cattan, 2002; Cattan and Dulcire, 2003). The competitiveness of Guadeloupean banana production on world market is low. This is due to higher labour costs than in other areas and to the decrease in public subsidies following the liberalization of the European banana market. This lack of competitiveness is reinforced by the intensification of the technical practices during the last two decades, based on monocropping, ploughing and use of expensive chemical inputs, in particular to control the endoparasitic nematode *Radopholus similis*, which is the main pest of the banana crop (Chabrier et al., 2003). These practices have led to yield loss (Clermont Dauphin et al., 2004), chronic lack of cash flow, water and soil contamination (Bonan and Prime., 2001; Bocquene et al., 2005) and erosion of farm income (Bonin and Cattan, 2006). Combined with an increasing social pressure for more environmentally-friendly practices and with the prohibition of numerous biocides, this situation has led farmers to an economic and technical crisis. As a result, the number of banana farmers has decreased drastically, from about 1400 farms (and 8000 ha) in 1981 to about 220 farms (and 3000 ha) in 2006. This drastic decrease threatens the local economy, as banana export is an important source of income and employment for this Caribbean island. Current banana management systems therefore need to be adapted to this new situation.

Following the method presented above, we first conducted a survey on a random selected sample of 66 farms from a first stratification of total population of banana growers according to soil type and farm size, two factors that can be responsible for a great variability of technical, economic and biophysical constraints. This represents a sampling rate of about 36%. Survey consisted of two successive face-to-face interviews with a farmer, each lasting from 3 to 5 hours. The interviews were divided into three parts, allowing for a general description of the farmer's CMS, CMSC, and CMSP. An exhaustive presentation of the 33 qualitative and 13 qualitative variables used in the survey's questionnaire is given in the **table 1**. Variables for describing a CMS are relative to the most representative banana's crop management system on the farm and to the decision rules for the crop pattern of banana (REP, DES, ANE and ROT), sowing modality (DES, PLO, VPL), management of banana fields in terms of shoot density (REP and ANC), chemical inputs application (QFE, FFE, HER, NEM), operations for the management of banana quality (FLO), and frequency of harvesting (PAC). Descriptive variables of CMSCs are relative to the physical context (SOI, ALT, MEC, SLO), resource endowments such as land characteristics (TEN, SUB, IRR, LAN), financial capacities (EXI, CAS, INV, NFA), laborforce characteristics (MPC, FAM, TEM), the nature of the farming system (BAN and DIV), and socio-demographic and personal characteristics (PRO, STU, INF, AGE). CMSPs were described with indicators of agronomic perfomance (CYC, MAT, YIE, BUN, REJ, QUA), economic performance (EFP, WOR, PCO, BNM), and potential environmental impacts (AMP). The statistical treatments used to design the typology (PCA, AHC, descriptive statistics, and CA) were made with the software package SAS 9.1 (SAS Institute Inc., 2004). The panel of local experts involved to define prototypes was composed of 6 scientists working on banana cropping systems in the areas of soil science, crop nutrition, nematology, genetics, economics, and farming system research. Experts were brought together in five meetings that lasted between 2 and 4 hours.

2.3. Results

2.3.1. Typology of banana farms in Guadeloupe

Characteristics of the farm typology

The PCA allowed us to reduce the number of dimensions in the quantitative data by selecting the first eleven components of the PCA which explain 77% of the total variability. The analysis of the contribution of the initial variables to the first two components of the PCA which supports 32% of the variability illustrates two main trends in the data (see **figure 2**). The right part of the first axis corresponds to farms with intensive practices (REP, AMP, FFE, VPL, BUN, ANC), favorable economic and physical context (LAN, NFA, MEC) and good agronomic, technical and economic performance (YIE, QUA, PAC, EFP, BGM). These situations are associated with high production costs (PCO), full-time and non familial workers, that are more expensive (see the opposition between FAM and TEM on the one hand and MPC and LAN on the other). The second axis discriminates between lowlands and uplands (ALT), where slope (SLO), banana cycle duration (CYC), and the possibility of mechanized ploughing is reduced (MEC). Uplands seems to be associated with a higher percentage of non commercialisable bananas (REJ) and with an earlier maturation of banana (MAT).

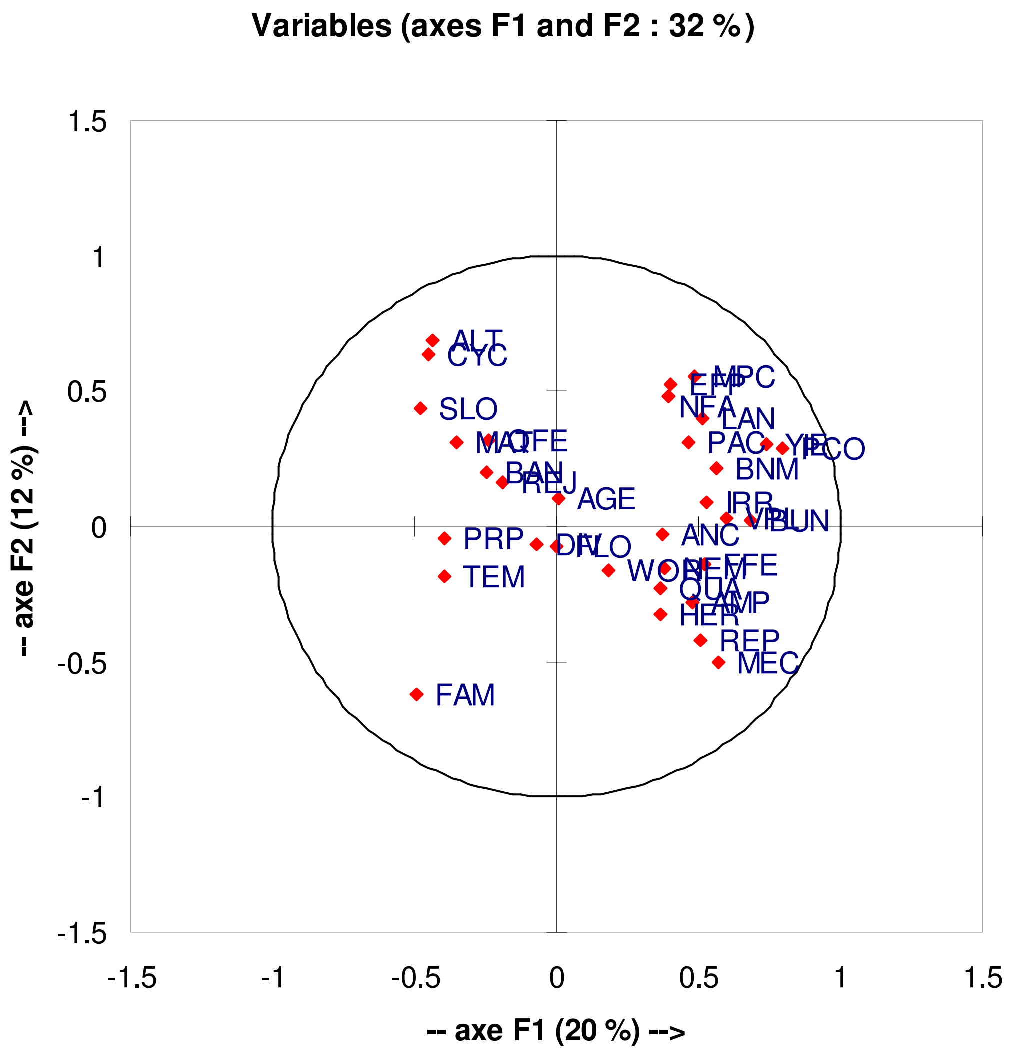

Figure 2. Representation of the initial variables used for building the typology in the correlation circle for the first two factors of the principal component analysis.

The uses of the principal components of the PCA in an AHC algorithm allowed us to obtain a typology with 6 farm types (**figure 3**). The truncature of the dendrogram in 6 classes of farms in the AHC algorithm allowed reduction by 96% of the overall dissimilarity level. Using descriptive statistics of the different groups and several trial and error tests on the level of truncature, we finally retained a truncature in 6 classes because it was the most satisfactory tradeoff in terms of inter-group dissimilarity and intra-group homogeneity. However, there still exists a degree of proximity between types 1 and 2, 3 and 4, and 5 and 6 indicating that these different types have some common characteristics.

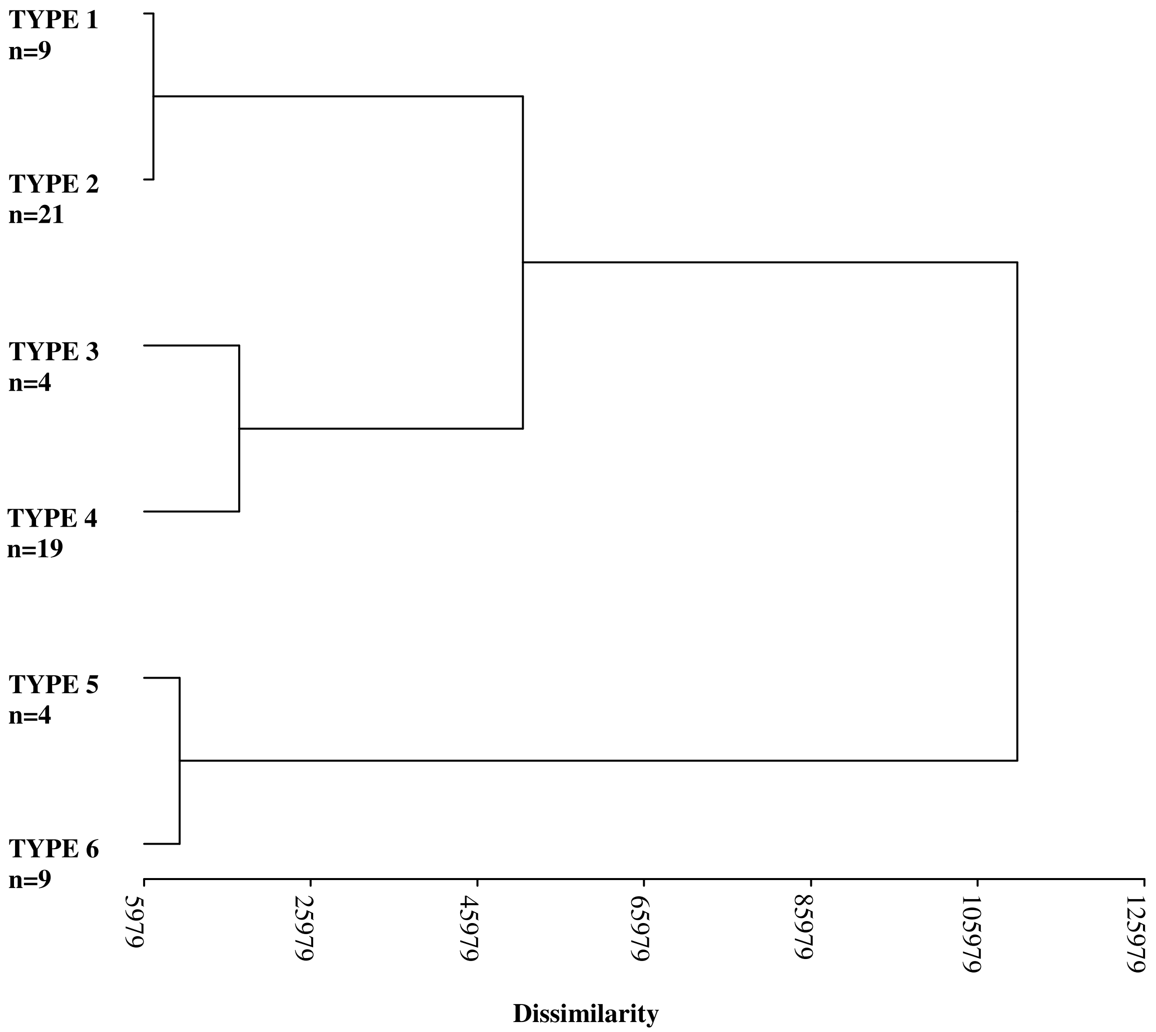

Figure 3. Dendrogram truncated after fifth level for the grouping of farms into six farm's types.

The typology was validated by applying it to a CA with the qualitative variables that showed a similar discrimination of farms according to the farm types and their relative position was exactly the same as in the dendrogram because type 1 and 2 were close, as well as type 3 and 4, and types 5 and 6, with a good discrimination between these three groups of farms.

Characteristics of the different farm types in terms of CMSs, CMSCs, and CMSPs

- **CMS:**

The average characteristics of the most representative banana crop management system (CMS) of each farm type are presented in **table 2**. We can see two main levels of differentiation among types which generate three main types of banana CMSs in Guadeloupe.

Category	Subcategory	Code	Mean or mode TYPE 1	Mean or mode TYPE 2	Mean or mode TYPE 3	Mean or mode TYPE 4	Mean or mode TYPE 5	Mean or mode TYPE 6
Banana Crop Management System (CMS)		DES	mechanical	mechanical	mechanical	chemical	0	0
		PLO	mechanical	mechanical	mechanical	mechanical	manual	manual
		ROT	0	0	1	1	0	0
		ANE	1	0	1	1	0	0
		REP	21%	15%	15%	16%	0%	0%
		VPL	50%	40%	100%	90%	0%	0%
		QFE	100	100	105	100	205	100
		FFE	12	9	17	12	3	6
		HER	4.8	6	5	6	0	4
		NEM	1	1.5	2.5	1	0	1
		PRP	11%	11%	9%	5%	12%	15%
		FLO	47	32	44	38	32	43
		ANC	50%	80%	100%	100%	15%	7%
		PAC	39	52	52	52	39	31
Context of banana Crop Management System (CMSC)	economic resources	TEN	1	0	1	1	1	1
		SUB	0	1	0	0	0	0
		EXI	0	0	1	1	1	0
		CAS	0	0	1	0	0	0
		INV	0	0	1	1	0	0
		LAN	4	10	82	28	8	6
		IRR	0%	0%	100%	0%	0%	0%
	farming system	NFA	1	1	3	1	1	1
		MPC	33	46	61	57	41	38
		BAN	71%	83%	82%	64%	95%	95%
		DIV	21.1%	10.0%	10.0%	16.8%	15.0%	18.9%
	physical context	SOI	nitisol	ferralitic	nitisol	andisol	andisol	andisol
		ALT	80	115	123	250	550	380
		MEC	100%	100%	100%	75%	0%	0%
		SLO	10%	0%	10%	10%	20%	30%
	personal ambition	PRO	diversification	diversification	stabilization	stabilization	abandonment	establishment
	social	STU	0	1	2	1	2	0
		INF	0	0	2	2	0	0
		AGE	53	47	58	49	59	46
		FAM	74%	42%	2%	9%	37%	70%
		TEM	12%	15%	0%	0%	45%	14%
Perfomance of banana Crop Management System (CMSP)	agronomical	CYC	9	9	8	10	12	11
		MAT	1.00%	1.00%	2.00%	1.00%	4.50%	2.00%
		YIE	21.4	22.5	45.2	38.5	17.3	18.6
		BUN	0.85	1.00	1.25	1.20	0.70	0.81
		REJ	15%	9%	18%	9%	28%	12%
		QUA	0.54	0.51	0.57	0.55	0.33	0.51
	economic	EFP	13.9	18.2	38.3	25.2	21.8	16.9
		WOR	162.2	128.3	139.6	156.5	84	122.6
		PCO	16 329	18 469	29 597	25 648	13 349	14 807
		BNM	499	885	9 676	5 654	-813	-404
	environnemental	AMP	7.5	15.5	17.5	10.2	0	8.4

Note: Table gives the mean value for quantitative variables, and the modal value for qualitative ones.

Table 2. Characteristics of the six farm types.

Types 5 and 6 are characterised by a perennial management with no replanting and very little anchorage of banana plants, which differs from all other types where farmers replant their fields every 5 to 8 years. Type 1, 2, 3 and 4 practice regular replantation of their banana fields with mechanized ploughing (REP, MEC). However types 1 and 2 differ from types 3 and 4 as they do not practise any crop rotation (ROT), and do not use only tissue culture plants for replanting (VPL) and systematic banana anchorage after flowering (ANC). Type 3 is the most intensive, with on average 17 applications of fertilizer (FFE) and 2 to 4 nematicide applications each year (NEM). By contrast, Type 5 is very extensive with manual weeding, no nematicide treatment, and only 3 fertilizer applications per year, but with a higher quantity of fertilizers for each treatment (QFE). All other types use 5 to 6 herbicide applications each year. Types 1, 5 and 6 harvest less than one time per week (PAC). Quantity of work for quality control (FLO) are similar across farm types.

- **CMSP**

Table 2 shows that banana yields of types 1, 2, 5 and 6 are all below 25 t ha^{-1} $year^{-1}$, which is very low compared to the potential yield in Guadeloupe which is about 50 to 60 t ha^{-1} $year^{-1}$ (Lassoudière, 2007). Type 3 is the most productive and economically efficient (BNM, YIE, BUN). Production costs are high for every farm due to the high labour requirement (PCO), at least 0.35 full-time man equivalent unit per hectare, for banana production and packaging (WOR). Types 3 and 4 are highly efficient with high efficiencies at packaging (EFP), which could be explained by a better level of equipment and a higher specialisation of the workers. Potential environmental impacts range from very low (for type 5) to high for types 2 and 3 with more than 15 kg per hectare of active ingredient applied each year as herbicides and nematicides (AMP).

- **CMSC**

Types 1 and 2 are exclusively located in the lowlands where the rainfall can be limiting, and have no access to irrigation. Type 1 corresponds to small farms (LAN = 4ha), with an average rate of 74% of family sourced manpower. These rates decrease to 42% for farm Type 2, which is medium sized (10ha), but with a non total land tenure, and a fractionned farm area. Both types have financial limitations with no capacity for investment, a restrictingly low level of cash flow, and poor access to information. By contrast, farm Type 3 corresponds to large farms with an average acreage of 82 ha. This too is a lowland type, located on ferralitic or nitic soils, but with access to irrigation. Types 1, 2 and 3 are located at the foot of the mountains in an area where mechanization is possible. This could explain why they practise regular replanting and so choose mostly purchased nematode-free plants for replanting as the latter can considerably reduce plantation time. Type 4 is mainly located between lowlands and uplands on andisols with an average rate of 75% of fields mechanizable, and an average acreage of 28 ha. Types 3 and 4 are characterized by better access to information, external income and investment capacities (INV, EXI, INF, STU). They differ from the other types in that their workers have full-time status, and are better paid (see FAM, TEM and MPC). This can be explained by the large acreage of these farms which thus need permanent external workers that are socially structured into unions, and more expensive than family-sourced manpower. Type 3 is the only one with no cash flow limitations at any moment of the year.

Type 5 is located exclusively in the uplands with an average altitude of 530 m.a.s. (see ALT in **table 2**). Type 6 is also an upland type, with an average altitude of 380 m.a.s. Types 5 and 6 are located in zones where rainfall is high (more than 4000mm per year) and are also characterized by the presence of steep slopes (SLO between 20 and 30%). These physical conditions make it possible therefore to understand CMSs of types 5 and 6, with no mechanization (this is not possible due to high rainfall and steep slopes), and perenial management (replantation is very labor intensive as mechanization is not possible for ploughing). By contrast with farm type 6, farm Type 5 is characterized by situations where farmers are older and have no prospect of farm transmission, which may account for their prospect of retirement and farm abandonment.

All farm types are highly specialised in banana production (see variable BAN in **table 2** that is always superior to 60% with an average value of 75% for all the farms of the sample).
Small land area and low yields may explain why types 1, 5 and 6 all harvest less than 52 times per year, as their weekly banana production is not sufficient to fill an entire banana container. The low cost of labour associated with types 1, 2, 5 and 6 (MPC) could be explained by the higher percentage of family labour in the total workforce (FAM), and may explain why these systems can survive to the market crises despite strong financial limitations and low yields.
This description by farm types well illustrates the diversity of constraints at farm level and their hybrid nature (biophysical, economic and structural).

2.3.2. Prototyping innovative banana crop management system

Objectives and biotechnical functions for prototyping more sustainable CMS

The characterization of the performance of the CMSs in Guadeloupe (CMSPs) allowed the experts to define two main objectives for improving the sustainability of current CMSs: 'reducing pesticides use (O1), and 'improving natural control of pests and/or plant mineral nutrition in bananas in order to maintain or improve yield (O2). O1 is consistent with the societal demand in Guadeloupe, where banana-based farming systems are located close to human habitat, as they could preserve water quality from pesticide contamination (Bonan and Prime, 2001). According to the panel of experts, objective O2 could render better banana yields and thus better economic results, while reducing the use of chemical inputs. This objective is particularly relevant for farm types 1, 2, 5 and 6 whose yields are low. Then the experts proposed 6 simple biotechnical functions seen as ways of achieving O1 and O2. These functions, their targeted objectives and the relevent farm types for these objectives are presented in **table 3**.

Agro-ecological objectives	Functions mobilizable to achieve objectives	FARM TYPE 1	FARM TYPE 2	FARM TYPE 3	FARM TYPE 4	FARM TYPE 5	FARM TYPE 6
O1: reducing pesticide use	Reduce nematicide		X	X			
	Reduce herbicide	X	X	X	X		X
O2: improving natural control of pests and/or mineral nutrition	Natural control of nematode	X	X			X	X
	Improving crop tolerance to nematodes	X	X			X	X
	Natural control of weeds	X	X	X	X	X	X
	Nitrogen fixation		X			X	X

Table 3. Agro-ecological objectives for the prototypes, associated mobilizable biological or technical functions and concerned farms' types.

It is obvious that these two objectives are not mutually independent, as improving natural control of pests (O2) could help reduce pesticide use (O1). However experts thought that some innovations could fulfil O1 without fulfilling O2 and still be relevant for some situations. O1 is relevant for farm types 2 and 3 because of its high level of nematicide use (about two applications each year on average) which is harmful for the environment. Reducing herbicide uses however concerns all farm types except farm type 5 as they all practice more than 4 applications each year.

Types of innovations	Nature of Prototype	Prototype code	Agro-ecological objectives					
			O1: reducing pesticide use		O2: improving natural control of pests and/or mineral nutrition			
			Reduce nematicide	Reduce herbicide	Natural control of nematode	Improving crop tolerance to nematodes	Natural control of weed	Nitrogen fixation
A. Pesticideregulations	Withdrawal of nematicide use	A1	X					
	Withdrawal of herbicide useand mechanical weeding	A2		X				
	Withdrawal of nematicide and herbicide use and mechanical weeding	A3	X	X				
B. Rotation or improved fallow and withdrawal of nematicide use during three years after banana plantation	8 months of improved fallow with *Crotalaria juncea* before replanting	B1	X		X			X
	12 months of chemically controlled fallow before replanting	B2	X		X			
	18 months of rotation with pineapple	B3	X		X			
C. Intercropping and withdrawal of herbicide use	Intercropping with *Canavalia ensiformis* and mulching at flowering	C1		X			X	X
	Intercropping with *Brachiaria decumbens* and mechanical mowing	C2		X			X	
	Intercropping with *Impatiens sp*	C3		X			X	
D. Reasonment of chemical input application	Nematicide treatment as a function of nematode pressure	D1	X					
	Herbicide treatment as a function of soil cover	D2		X				
E. Hybrid cultivars and withdrawal of nematicide	Cultivar type 1	E1	X			X		
	Cultivar type 2	E2	X			X		
F. Integrated systems with partial or total (F3) withdrawal of pesticide use	12 months of improved fallow with *B. decumbens* before replanting + no tillage + intercropping with B. decumbens	F1	X	X	X		X	
	12 months of natural chemically controled fallow before replanting + Intercropping with *Impatiens sp.*	F2	X	X	X		X	
	Cultivar type 2 + 8 months of improved fallow with *C. juncea* before replanting + Intercropping with *C. ensiformis* and mulching at flowering + organic fertilization	F3	X	X	X	X	X	X

Table 4. Prototypes and associated agro-ecological objectives.

Improving natural control of nematodes or improving crop tolerance to nematodes was identified as important for types 1, 2, 5 and 6 that have no strategy for managing parasitic pressure as they do not practice rotation, and use few nematode free plants at replantation. Natural control of weeds is relevant for all farm types, including farm type 5 which does not use herbicides but uses a lot of labour for weed control. Nitrogen fixation was considered relevant for farm types 2, 5 and 6 that under-fertilise, according to the experts, because of their climatic and technical situations.

Defining a priori totally compatible prototypes

According to the different objectives, biotechnical functions and CMSC identified and with the use of the compatibility indicator, the experts' final meetings yielded 16 technical prototypes mobilizing the 6 biotechnical functions (see **table 4**). Innovations that were chosen by the experts can be put into 6 categories according to their nature: pesticide regulation (A), adoption of rotation or improved fallows in the banana crop pattern (B), intercropping bananas with cover crops providing environmental services to bananas (C), decision rule modification for integrated management of chemical inputs (D), adoption of hybrid banana cultivars (E), and integrated crop management systems (F) which combine several of the technical innovations A to E. CMS prototypes of type A and D make possible the fulfilment of objective O1 only, while types B, C, E and F make it possible to fulfill both O1 and O2 objectives. Prototype F3 is the most innovative as it combines both the use of hybrid cultivars, improved fallow, intercropping, and organic fertilization. On the other hand, prototypes A1, A2, A3, D1 and D2 consists of a single decision rule entailing a modification of the current CMS for each farm type.

Table 5 presents the 6 different CMSCs identified for the different farm types. The five constraints identified by the experts are based on hypotheses formulated on potential negative interactions between the prototypes and the socio-economic and environmental factors of the CMSC. In each CMSC the constraints may differ in nature and number. Each farm type has at least one constraint (farm type 4), type 1 and 6 being the most restricted, with the presence of 3 out of the 5 identified constraints. It is interesting to pinpoint the diversity in the nature of constraints in each CMSC, hence confirming the need to consider them together as a consistent set as proposed by Lançon et al. (2007).

Table 6 shows the result of the confrontation of each prototype with the various farm types of the typology characterized with their CMSCs. Within one innovation type each prototype variant has different characteristics that are compatible with different constraints.

Constraints	FARM TYPE 1	FARM TYPE 2	FARM TYPE 3	FARM TYPE 4	FARM TYPE 5	FARM TYPE 6
Risk of water deficit	**1**	**1**	0	0	0	0
Non mechanizable land	0	0	0	0	**1**	**1**
Impossibility to reduce manpower	0	0	**1**	0	0	0
Impossibility to increase work arduousness	0	0	**1**	0	0	0
Limited land availability	**1**	0	0	0	0	**1**
Financial limitations	**1**	**1**	0	**1**	**1**	**1**

Note: Element T(w,y) of matrix T is equal to 1 if constraint w is present in farm type y, 0 otherwise.

Table 5. Matrix of constraints defined for each type of CMSC.

		Risk of water deficit	Non mechanizable land	Impossibility to reduce manpower	Impossibility to increase work arduousness	Limited land availability	Financial limitations
A. Pesticides regulations	**A1**	0	0	0	0	0	**1**
	A2	0	0	0	0	0	**1**
	A3	0	0	0	0	0	**1**
B. Rotation or improved fallow	**B1**	0	**1**	0	0	0	**1**
	B2	0	0	0	0	**1**	0
	B3	0	**1**	**1**	**1**	**1**	0
C. Intercropping	**C1**	0	0	0	**1**	0	0
	C2	**1**	**1**	0	0	0	**1**
	C3	**1**	0	0	**1**	0	0
D. Reasonment of chemical inputs application	**D1**	0	0	0	0	0	**1**
	D2	0	0	0	0	0	0
E. Hybrid cultivars	**E1**	0	0	**1**	**1**	0	**1**
	E2	0	0	0	0	0	**1**
F. Integrated systems	**F1**	**1**	**1**	0	0	**1**	**1**
	F2	**1**	0	0	**1**	**1**	0
	F3	0	**1**	0	**1**	0	**1**

Note: Element I(x,w) = 1 for prototype x and constraint w, if prototype x is likely to increase the expression of constraint w, 0 otherwise.

Table 6. Sensitivity of the expression of constraints to prototypes.

For instance, fallow with *C. juncea, which* is a short 8-month non productive but costly crop (for soil ploughing and purchase of seeds), is adapted to CMSCs where mechanization is possible and there are no financial limitations.

Table 7 presents the level of compatibility of each prototype with each farm type measured, with the compatibility indicator (CI) between the CMS and the constraints of the CMSC. This indicator varies from 0 to 1 in each farm type, showing that some prototypes are not compatible with any of the constraints of this farm type (CI=0), while others are totally compatible (CI=1). Each farm type has several prototypes totally compatible with its CMSC, but the number differs greatly, between 2 for farm Type 1 to 10 for farm Type 3.

Each prototype is totally compatible with at least one farm type, except E1 and F3. Even if these prototypes are very interesting from an environmental point of view they would likely increase constraints for all farms. Prototype E1 is a hybrid cultivar characterised by a shorter cycle, smaller bunches, and an great height (from 4 to 6 meters). It was associated by the experts with two constraints of which at least one is present in each farm type. Experts considered it as very probably linked to an increase of work arduousness, despite a global decrease in workload due to lower productivity reducing the workload for packaging. Prototype F3, providing many agro-environmental benefits, is very innovative as it combines the use of hybrid cultivar E2, improved fallow with *Crotalaria juncea*, intercropping with *Canavalia ensiformis*, and organic fertilization. The other integrated systems were found totally compatible with farm type 3 (F1) and type 4 and 5 (F2).

2.4.Discussion

Compared to other methods of prototyping alternative crop management system (Vereijken, 1997; Lançon et al., 2007), the method we proposed shares common steps such as “definitions of objectives” or “identification of prototypes with experts”. The originality of our method is that it makes it possible to take into account farm diversity, through a simple transparent and step by step procedure combining the use of a farm typology and expert knowledge. The method can be implemented with few resources (2 persons over 8 months) as it is based only on a farm survey on a sample of farms and on meetings with experts. The feasability of the application of this method is however dependent upon the existence of a panel of local experts with a good knowledge of the cropping system that is to be improved, and of alternative cropping techniques.

Types of innovations	Prototype's nature	Innovations' code	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
A. Pesticideregulations	Withdrawal of nematicide use	A1	0.7	0.5	**1.0**	0.0	0.5	0.7
	Withdrawal of herbicide useand mechanical weeding	A2	0.7	0.5	**1.0**	0.0	0.5	0.7
	Withdrawal of nematicide and herbicide use and mechanical weeding	A3	0.7	0.5	**1.0**	0.0	0.5	0.7
B. Rotation or improved fallow and withdrawal of nematicide use during three years after banana plantation	8 months of improved fallow with *Crotalaria juncea* before replanting	B1	0.7	0.5	**1.0**	0.0	0.0	0.3
	12 months of chemically controlled fallow before replanting	B2	0.7	**1.0**	**1.0**	**1.0**	**1.0**	0.7
	18 months of rotation with pineapple	B3	0.7	**1.0**	0.0	**1.0**	0.5	0.3
C. Intercropping and withdrawal of herbicide use	Intercropping with *Canavalia ensiformis* and mulching at flowering	C1	**1.0**	**1.0**	0.5	**1.0**	**1.0**	**1.0**
	Intercropping with *Brachiaria decumbens* and mechanical mowing	C2	0.3	0.0	**1.0**	0.0	0.0	0.3
	Intercropping with *Impatiens sp*	C3	0.7	0.5	0.5	**1.0**	**1.0**	**1.0**
D. Reasonment of chemical input application	Nematicide treatment as a function of nematode pressure	D1	0.7	0.5	**1.0**	0.0	0.5	0.7
	Herbicide treatment as a function of soil cover	D2	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
E. Hybrid cultivars and withdrawal of nematicide and fungicides	Cultivar type 1	E1	0.7	0.5	0.0	0.0	0.5	0.7
	Cultivar type 2	E2	0.7	0.5	**1.0**	0.0	0.5	0.7
F. Integrated systems with partial or total (F3) withdrawal of pesticide use	12 months of improved fallow with *B. decumbens* before replanting + no tillage + intercropping with B. decumbens	F1	0.0	0.0	**1.0**	0.0	0.0	0.0
	12 months of natural chemically controled fallow before replanting + Intercropping with *Impatiens sp*.	F2	0.3	0.5	0.5	**1.0**	**1.0**	0.7
	Cultivar type 2 + 8 months of improved fallow with *C. juncea* before replanting + Intercropping with *C. ensiformis* and mulching at flowering + organic fertilization	F3	0.7	0.5	0.5	0.0	0.0	0.3
Total number of prototypes totally compatible with farm's type's CMSC			**2**	**4**	**10**	**6**	**5**	**3**

Table 7. Compatibility indicators values between prototypes and farm type.

The total duration of the meetings with experts in the application of the method to the prototyping of banana based cropping system in Guadeloupe was about 15 hours, which is time consuming for the experts but affordable if included in a regional program of development.
The results of the method can be sensitive to several parameters whose implications have to be discussed. Firstly, the choice of the variables and of the sample of farms has to be made cautiously as they can influence the identification of the constraints of the CMSCs by the experts and the coverage of regional diversity. In the design of the typology, some emphasis can be given to a specific part of the CMS (e.g. fertilisation practices) or to a specific farm type (e.g. the most intensive), but this would reduce the usefulness of farm typology for other questions. Secondly, the experts' decisions are of considerable importance, because they are involved at each step of the prototyping framework (definition of objectives, CMSCs and prototypes). However, in order to enlarge the knowledge base on the CMSs and the viewpoints on their assessment it would be better to extend the panel of experts to other stakeholders such as farmers, fruit companies and policy makers. It is also advised to combine various scientific disciplines like, agronomy, soil science, phytopathology, genetics, economy, sociology, and ecology, in order to define multi-objective and multi-constraint innovative CMSs. In our method, all experts are involved in every task of the second step. This can be justified by the fact that assessing the compatibility of one innovation with a farm requires multidisciplinarity. However we can imagine that if consensus on the choices to be made is hard to reach, it would be better to involve experts at different stages according to their competency area.
The Compatibility Indicator and the matrix with which it is assessed are useful to help experts identify innovations that are totally compatible with a farm's constraints. However, comparing the compatibility of a given prototype among several farm types does not make sense, as this indicator is highly dependant upon the number of constraints considered on the one farm. Although it is quantitative because it combines different constraints in a quantitative global indicator, it traduces the individual presence and the expression of each constraint in a binary manner. It could be useful to assess quantitatively the presence and expression of constraints, because a given constraint can be more or less problematic depending on the farm type. Finally we could also improve the method by defining several horizon temporal for the definition of the constraints, and thus differentiate the tactical constraints from the strategic constraints. Similarly, we could also consider different contexts of policy and market outlook for defining prototypes.

The method applied to the prototyping of more sustainable crop management systems in Guadeloupe showed the existence of 6 farm types covering a wide diversity of CMSs whose sustainability needs to be improved at different levels. This diversity corresponds to different economic, physical and social farm contexts, hence confirming the interest for a well formalized methodology capable of taking into account heterogeneous farming situations in the design of more sustainable cropping systems. A wide variety of innovative techniques was required to mobilize several biotechnical functions at field level. It showed that within a type of prototype (A, B, C, D, E or F), it was necessary to develop different variants to satisfy different CMSCs. To define at least one prototype compatible for each farm type, 16 very different prototypes were defined, although the final number of totally compatible prototypes varies considerably between farm types from 2 to 10.

Although only two iterations were made in our study to improve the level of compatibility between prototypes and farm types, it led to the definition of three different variants of rotations, three ways of intercropping bananas with different cover crops, and three integrated systems combining rotations and intercropping. Thanks to this approach, at least one specific intercrop, *a priori* totally compatible, was found for each farm type in order to control weed pressure and reduce herbicide use. We must observe, however, that no satisfactory rotations were found for farm type 1 and 6.

Types 5 and 6 have very limited scope for adopting crop rotations, because they have steep slopes that make rotations involving mechanical ploughing not feasible. For this reason B2 seems to be the most adapted to these situations.

The application of the method to the Guadeloupean case was a first step in a prototyping research program at regional level. As a contribution to this program, this study yielded a conceptual model of farm diversity and a corresponding set of innovations to be assessed. Testing the 16 prototypes on the 6 farming situations would represent 96 situations to be assessed, which would be costly with experimental trials. In our study applied to Guadeloupe, the compatibility index enabled us to reduce the number of 'prototype * farm type situations' to be assessed to 30. However this is still too many and too costly to implement asan experiment-based approach emphasizing the need to develop bio-economic models combined with farm typology (Sterk et al., 2007; Van Ittersum et al., 2007). Integrating farm diversity in farm or crop models to virtually assess prototypes is not easy and entails several methodological issues, like the contextualisation of the prototype's impacts on each farming system. The method proposed in this paper could make this model-based assessment more efficient by providing a systemic characterization of both innovative and current CMSs and the environment in which they have to be assessed.

2.5. Conclusions

To take into account farmer's constraints in the prototyping of an alternative crop management system (CMS), we propose a step by step method combining the use of a farm typology and expert knowledge. Using a systemic and typological approach to the diversity of current CMSs through a survey on a sample of farms, the method made it possible to model farm diversity in terms of CMS, physical, economic and social contexts (CMSCs), and performance (CMSP). This characterization allowed experts to define step by step relevant objectives and techniques to improve the CMS sustainability at the territorial level, and to define the CMSC of each farm type into which the CMS prototypes must be assessed. Using a compatibility indicator aimed at assessing the level of compatibility between prototype and farm type, the method allowed us to blend agro-ecological knowledge from different scientific disciplines into a coherent work agenda for designing prototypes adapted to the different farm types. The method is simple but requires the involvement of a panel of experts having sufficient knowledge of the CMSs and of how to improve their performance in a farm sustainability context. The results are also dependent upon the choice of the variables for building the farm typology, and on the experts' choices, that must be made cautiously and in a transparent manner. Our methodology applied to Guadeloupean banana farmers has led to the definition of 16 different prototypes involving different types of innovations and providing different environmental services. Even if the *a priori* totally compatible prototypes may vary considerably in nature and number among farm types, the method enabled us to find at least two totally compatible prototypes for each farm type.

Integrating this method into a participative prototyping approach could be useful as it is likely to ensure a better matching of the agricultural innovations to the farming situations, and thus improve their likelihood of adoption.

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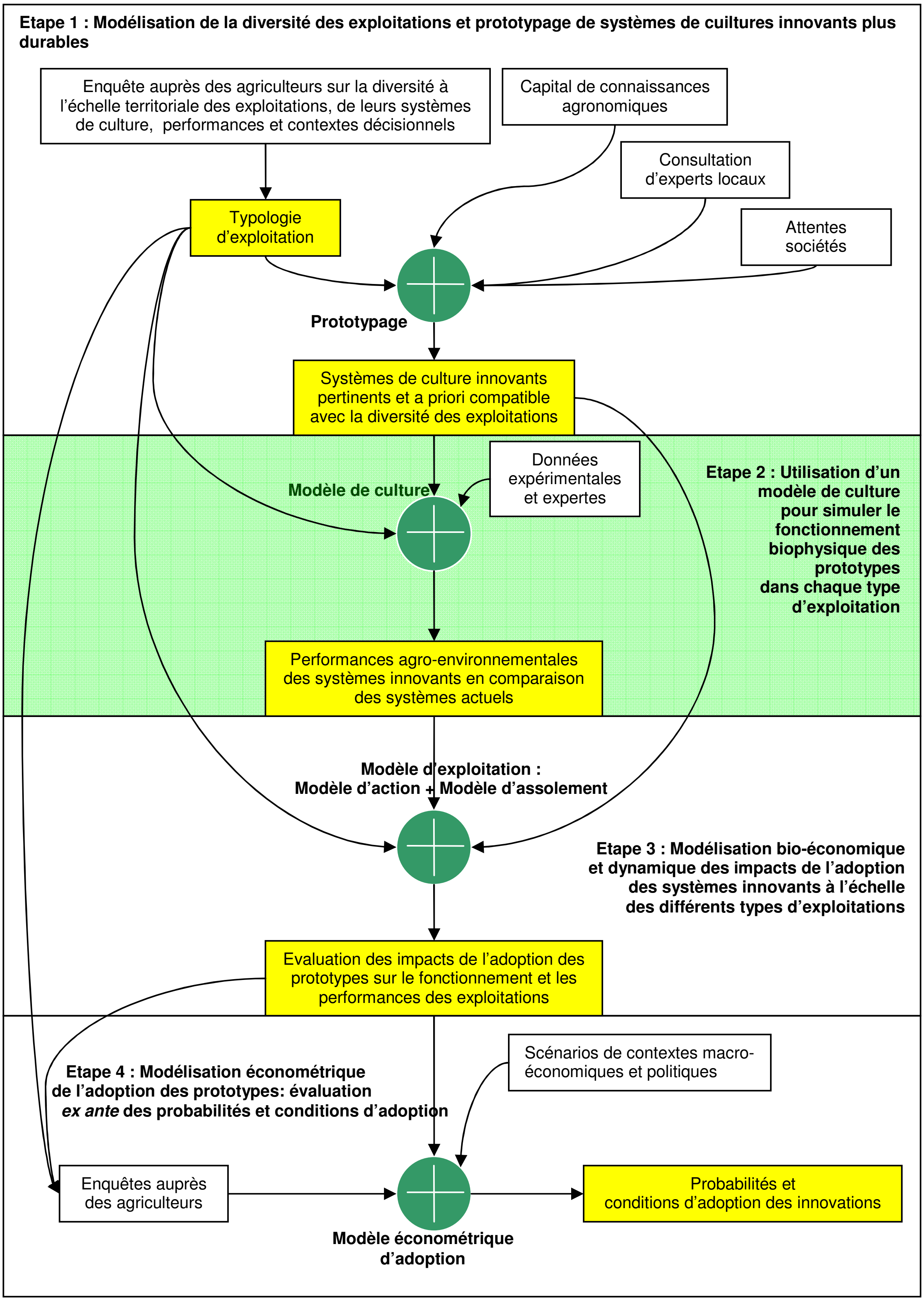

Figure B : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

3. Utilisation d’un modèle de culture pour simuler le fonctionnement biophysique des prototypes et les évaluer dans chaque type d’exploitation

Ce chapitre correspond à la description de la deuxième étape de la méthode (cf. figure B).

Cette étape a pour objectif d’utiliser un modèle de culture afin de simuler le fonctionnement biophysique des prototypes dans tous les types de ferme, qui ont été définis et caractérisés dans l’étape 1. A titre illustratif, quelques photos de prototypes de systèmes innovants sont présentées en annexe.

Cette deuxième étape est indispensable pour évaluer les performances agronomiques des prototypes en terme de rendement et d’usage de pesticides, et pour avoir une modélisation du comportement biophysique des systèmes de cultures (états du peuplement végétal à la parcelle et ses évolutions) qui permettra modéliser le fonctionnement de l’exploitation dans l’étape 3.

A cette fin, nous avons utilisé le modèle SIMBA développé par Tixier (2008a), que nous avons développé, calibré et paramétré.

La méthode proposée pour conduire cette deuxième étape ainsi que les résultats de son application à l’évaluation des prototypes dans les types d’exploitations sur les critères de rendement et d’usage de pesticide sont présentés dans l’article suivant, intitulé « **Model-based assessment of technological innovation in banana cropping systems contextualized by farm types in Guadeloupe.** », qui a été soumis à la revue ***European Journal of Agronomy*** (http://ees.elsevier.com/euragr/).

Model-based assessment of technological innovation in banana cropping systems contextualized by farm types in Guadeloupe.

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Abstract
Farmers are advertised about many innovations that are supposed to increase their yields or to reduce environmental impacts. Yet the performances of innovations depend on the farming context. Here, we present the *ad-hoc* adaptation of the crop model SIMBA to account for innovations previously selected through a typology of banana farming systems and the method to evaluate 16 innovations in six types of farms. The innovations include regulation about the use of pesticides, rotations and fallows, intercropping, conditional application of pesticides, resistant cultivars, and integrated systems. Our results show that for a given innovation, yield and pesticide reduction vary widely with farm type. We show that environmentally friendly innovations often cause more yield decrease in the more productive farm types. Nevertheless, despite an apparent trade-off between yield and pesticide uses, some innovations address both production and environmental issues, e.g. rotation with fallows improved with a cover crops, regular fallows, and rotations with pineapples for the most intensive farm types. Our modeling study confirms the importance of innovation-farm type interactions and the usefulness of models for assessing large numbers of technological innovations among a wide range of biophysical and technical contexts.

Keywords: low input innovation; crop model; farm typology; yield; pesticides; Guadeloupe; *Musa* spp.

3.1. Introduction

Given the increasing societal demand for more eco-aware farming practices, farmers are faced with choosing among a plethora of innovations, from new cultural practices or cultivars to new pest management planning. In addition to these complex choices, they have to make trade-offs between production, labor, subsidies, and environmental risks (Waller *et al.*, 1998). Methodologies for designing more sustainable cropping systems are of growing interest. It is now assumed that crop models are useful tools for designing innovative systems (Dogliotti *et* *al.*, 2003, 2004; Keating *et al.*, 2003; Loyce *et al.*, 2002a, 2002b; Sterk *et al.*, 2006; Stöckle *et al.*, 2003; Tixier *et al.*, 2008a). Nevertheless, published approaches often deal with new combinations of current cultural practices and rarely with new radical technical innovations. Furthermore, these approaches do not give attention to the diversity of farming situations to which the innovations are applied (Sterk *et al.*, 2007).

Some innovations might be very efficient in some farming contexts and completely inadequate in others (Orr and Ritchie, 2004), mostly because of environmental conditions, economic endowments and current farming systems, which vary widely among farmers (Bernet *et al.*, 2001). This context is poorly taken into account, and most agronomists tackle only one or few theoretical situations, which are far from reality and often not well described (Sterk *et al.*, 2007). Hence, the assessment of innovative cropping systems may be biased. Thus, evaluating *ex ante* the production and the environmental performances of innovations in the specific context of each farm type becomes an important part of prototyping new cropping systems that target high productivity and are harmless to the environment. This evaluation is the key point that helps researchers and stakeholders promote innovations to the farms where they are most suitable and to guide the dissemination and the adoption of innovations (Diederen *et al.*, 2003a). However, adopting an innovation also depends on many factors, e.g. social, economic, or personal (Edwards-Jones, 2006). Herein, we focus on production and environmental performances of innovative cropping systems.

When a farmer adopts an innovation, this innovation is integrated, with most frequently some adaptation, into its current cropping system. The result is an innovative cropping system specific to the farm type. The conditions of a farm include a biophysical context, i.e. climate, soil type, plant-parasitic pressure, and a technical context, i.e. level of inputs, labor, and technical knowledge. In a given production area, there is often a wide range of farm types; this diversity in farm types is generally even greater in tropical conditions. Technical innovations are the basis of progress in cropping systems; they include genetic innovations such as pest resistant varieties, intercropping, integrated pest management, new type of fertilization, or new crop rotations. Innovations provide different economic and ecological services, e.g. increased yield, reduced pesticide uses, and protection against erosion and runoff.

Throughout the world, banana production (*Musa* spp., AAA, Cavendish sub-group cv. Grande Naine) for export is mainly based on intensive monocropping systems. There is a wide range of production types, from organic to high input systems. But most intensive systems are not environmentally friendly. The agronomic and ecological sustainability of these systems is often hampered by a high level of root parasitism, including nematodes (Tixier et al., 2007b). Air, soil, and water quality may be adversely affected by the frequent applications of chemical pesticides that are required to control this parasitism and by soil and plant management practices that may lead to severe erosion. These risks are magnified in fragile, tropical, insular conditions such as those found in Guadeloupe, in the French West Indies (F.W.I., 16°15'N, 61°32'W), where inhabited areas, coral reefs, and rainforests are close to agro-systems (Bocquene and Franco, 2005; Bonan and Prime, 2001). This issue also concerns all areas of intensive production of banana (Castillo *et al.*, 2006; Chaves *et al.*, 2007; Matthews *et al.*, 2003). At the same time, managing the labor, adapting to a fluctuating and highly competitive market, and limiting pesticide use are major economic problems that threaten the whole banana production sector in F.W.I. (Bonin *et al.*, 2004). In the specific case of Guadeloupe, a wide range of farm types exists, from the intensive systems similar to the ones in intensive production areas of Latin America; to very extensive systems with very low inputs, similar to the ones in small rural farms context.

In this paper, we present the *ad-hoc* adaptation of the crop model SIMBA (Tixier et al., 2008a) to account for innovations previously selected through a typology of banana farming systems and the method to evaluate these innovations in different types of farms in Guadeloupe. The SIMBA model was chosen for this study as it allows to account for a wide range of technical operations. We then present a detailed evaluation of 16 innovations with regard to yields and pesticide uses for six farm types. We analyze the performances of these innovations relative to current cropping systems. In the perspectives, we highlight how model-based evaluation of innovation can interact with farmand landscape-scale prototyping methods. To our knowledge, this is the first time that a biophysical model-based approach is used to assess innovations accounting for the farming context.

	Variable	Unit	Farm type					
			1	2	3	4	5	6
Regional importance	Fraction of population	%	14%	32%	6%	28%	6%	14%
	Fraction of banana area	%	4%	14%	30%	44%	5%	3%
Banana management system	Rate of bananas area replanted each year	%	21%	15%	15%	16%	0%	0%
	Rate of seedlings which are produced by tissue culture and nematode-free	%	50%	40%	100%	90%	0%	0%
	Nitrogen applied per plant per application	Kg	0.100	0.100	0.100	0.100	0.205	0.100
	Number of nitrogen applications each year	yr^{-1}	12.0	9.0	17.0	12.0	3.0	6.0
	Number of herbicide treatments per year	yr^{-1}	4.8	6.0	5.0	6.0	0.0	4.0
	Number of nematicide treatments per year	yr^{-1}	1.0	1.5	2.5	1.0	0.0	1.0
	Rate of banana plants replaced each year	%	11%	11%	9%	5%	12%	15%
	Amount of post-flowering work to bunches for banana quality management	$d\ ha^{-1}\ yr^{-1}$	47	32	44	38	32	43
	% of flowered plant cabled for bunch weight support	%	50%	80%	100%	100%	15%	7%
	Type of destruction of banana fields: mechanical, chemical, or manual	-	mechanical	mechanical	mechanical	chemical	none	none
	Type of tillage at plantation : mechanical or manual	-	mechanical	mechanical	mechanical	mechanical	manual	manual
	Rotation presence : equals 1 if fallow or rotations; otherwise 0	-	0	0	1	1	0	0
	Fungicide treatments: equals 1 if fungicide treatments are done otherwise 0	-	1	1	1	1	0	0
Cropping system performances	Average yield of banana cropping system	$t\ ha^{-1}\ yr^{-1}$	21.0	23.5	46.0	38.5	15.8	18.5
	Amount of active mater of biocides applied each year	$Kg\ ha^{-1}$	26.8	30.4	29.7	22.9	0.0	12.1
	Annual profit margin	€ ha^{-1}	2097	760	4929	4849	-971	1235

Table 1. Characteristics of the banana management systems of the farm types in Guadeloupe.

3.2. Materials and methods

3.2.1. Current cropping systems and farm context

In Guadeloupe, banana-based cropping systems range from the very intensive to the very extensive ones. A typology of these cropping systems has been done (Blazy *et al.*, 2008b), and it led to the definition of six farm types (**Table 1**). The most intensive farm types (1, 2, 3, and 4) use a high level of fertilizer, pesticides, labor, and frequent replanting with plowing, and they are characterized by a wide range of agronomical performances (from 21 to 46 tons.ha^{-1}.year^{-1}). On the other hand, the less intensive farm types (5 and 6) are low-input perennial systems, less harmful to the environment, but they have a very low level of production (15.8 and 18.5 tons.ha^{-1}.year^{-1}). All these farm types also have different flexibility for innovation as they differ in production factors like labor, land, access to information, and financial resources. For this reason, a high number of modalities of innovation have been tested in this study. For this modeling study, we defined one theoretical farm for each farm type. For every technical decision rule and soil and climate condition, we selected the mean or the modal value of each farm type. These mean values were extracted from the 66-farm database used to build the typology (Blazy *et al.*, 2008b), in which each farm type has a very low intraclass variability.

3.2.2. Soil and climate conditions of banana-cropping systems in Guadeloupe

Table 2 presents the climate, soil, and topographic characteristics of each farm type. There is a correlation between the farm types we defined and the climate, i.e. the most productive types are at low altitude (below 300 meters for type 1, 2, 3, and 4), while the less productive types are at higher altitudes (above 300 meters for type 5 and 6). This distribution emphasizes the fact that the more competitive innovations cannot be the same for all farm types.

All the farms are on volcanic ash soils. Type 2 is mainly on ferralitic soils that are old and compacted, with 2795 mm of rain annually; this is the most susceptible to drought. Types 4, 5, and 6 are at higher altitude on andisols that are less evolved and characterized by fast drainage in areas that receive 3500 mm of rain annually; there is no risk of drought in this area. Type 1 and 3 are on nitisols, which are mid-evolved soils in areas that receive 2700 mm of rain annually, or below; on this area, there is a risk of drought, which is minimized by irrigation for type 3. For all these systems, root nematode pressures differ considerably (Clermont-Dauphin *et al.*, 2004).

Environmental condition variable	**Unit**	**Farm type**					
		1	**2**	**3**	**4**	**5**	**6**
Mean annual rainfall	$mm.yr^{-1}$	2614	2795	2700	3542	4118	4610
Mean sunlight	$MJ.m^{-2}.day^{-1}$	18.1	17.5	17.5	15.4	17.3	12.7
Soil type	-	Nitisol	Ferralitic	Nitisol	Andisol	Andisol	Andisol
Mean slope	%	10%	0%	10%	10%	20%	30%
Mean altitude	m	80	115	123	250	550	380

Table 2. Environmental conditions of each farm type.

3.2.3. Innovative cropping systems

Herein, we assessed 16 innovations: 13 single innovations (that concern only one component of the cropping system) and 3 integrated innovations that combine single innovations. **Table 3** presents the characteristics of the 16 innovations and their agro-ecological services. Innovations A1, A2, and A3 consist in stopping the use of pesticides (nematicides and herbicides); they can be considered as innovations based on extreme societal regulation in comparison with the current practices. Innovations, B1, B2, and B3 consist in rotations with fallows improved by cover crop (*Crotalaria juncea*), regular fallows that use herbicides, and a 18-month rotation with pineapple. These cover crops help reduce the plant-parasitic nematode population during fallows, thus shortening fallows before banana is planted. Innovations C1, C2, and C3 are based on intercropping with *Canavalia ensiformis*, *Brachiaria decumbens*, and *Impatiens sp.*; they are currently under investigation and their aim is first to reduce herbicide uses and second to improve soil nitrogen status. Innovations D1 and D2 are modifications of decision rules for application of nematicides and herbicides according to a monitored threshold of plant-parasitic nematodes and a percentage of soil covered by weeds. Innovations E1 and E2 are based on resistant cultivars; two types of resistant crops have been defined according to characteristics of synthetic hybrids under development (Abadie *et al.*, 2007; Bakry *et al.*, 2007).

Innovation type	Innovation description	Innovation code	Agro-ecological services						
			Reduce nematicide	Reduce herbicide	Reduce fungicid	Natural control of nematode	Natural control of weed	Nitrogen fixation	Improving crop tolerance to nematodes and fungs
A. Societal regulations	Nematicides’ stopping	A1	X						
	Herbicides’ stopping and mechanical weeding	A2		X					
	Nematicide and herbicides' stopping and mechanical weeding	A3	X	X					
B. Rotation or improved fallow	8 months of improved fallow with *Crotalaria juncea* before replanting	B1	X			X		X	
	12 months of chemically controlled fallow before replanting	B2	X			X			
	18 months of rotation with pineapple	B3	X			X			
C. Intercropping	Intercropping with *Canavalia ensiformis* and mulching at flowering	C1		X			X	X	
	Intercropping with *Brachiaria decumbens* and mechanical mowing	C2		X			X		
	Intercropping with *Impatiens* sp	C3		X			X		
D. Conditional application of pesticides	Nematicide treatment as a function of nematode pressure	D1	X						
	Herbicide treatment as a function of soil cover	D2		X					
E. Resistant cultivars	Cultivar type 1	E1	X		X				X
	Cultivar type 2	E2	X		X				X
F. Integrated systems	12 months of improved fallow with *B. decumbens* before replanting + no tillage + intercropping with *B. decumbens*	F1	X	X		X	X		
	12 months of natural chemically controled fallow before replanting + Intercropping with *Impatiens* sp.	F2	X	X		X	X		
	Cultivar type 2 + 8 months of improved fallow with *C. juncea* before replanting + Intercropping with *C. ensiformis* and mulching at flowering + organic fertilization	F3	X	X	X	X	X	X	X

Table 3. Main characteristics of the innovations.

These two types have been defined as resistant to the Sigatoka Disease and Black Leaf Streak Disease, caused respectively by *Mycosphaerella musicola* and *Mycosphaerella fijiensis*. In addition to these desired features, they are less susceptible to plant-parasitic nematodes, mostly burrowing nematodes (*Radopholus similis*) and lesion nematodes (*Pratylenchus coffeae*) than the classic Cavendish cultivars (Quénéhervé *et al.*, 2008). Finally, they have a different development and growth pattern, with shorter cropping cycle and smaller weight of bunch. They differ from each other for the level of these two characteristics. Three integrated innovations (F1, F2, and F3) were designed with a combination of rotations, intercropping, no-tillage, organic fertilization, or resistant varieties.

3.2.4. The SIMBA model and its new features

SIMBA simulates banana-cropping systems at field level over several cropping cycles. It includes sub-models that simulate soil structure, water balance, root nematode populations, yield, and economic outputs with a sound balance between representing the major processes of the system in the region and keeping the model simple to reduce the parameterization costs in a large range of conditions (Tixier *et al.*, 2008a). SIMBA and all its modules run at a weekly time-step at the field scale. All modules were calibrated using data previously collected in F.W.I. SIMBA was developed in the STELLA® software version 7.0.2 from Isee systems (formerly High Performance System ®). In SIMBA, all practices are described by 'decision rules', which are composed of a decision variable, a control variable, and an activation threshold or variation range. Such rules are coded with ‘if then else’ algorithms.

The main feature added in the SIMBA model for this study is the nitrogen balance module, SIMBA-N (Dorel *et al.*, 2008). The other main additional feature is the intercrop module SIMBA-IC, which is based on the simulation of leaf area index (LAI) and vegetative dry matter. The principles of this module are similar to those used in STICS (Brisson et al., 2004). The net primary production and the LAI are calculated based on the interception of the photosynthetically active radiation (PAR) accounting for the interception by the banana canopy. The percentage of nitrogen in cover crops is accounted for when they uptake mineral nitrogen from soil and when they restitute it to the soil organic pool. The nitrogen atmospheric fixation is also included in the SIMBA-IC module as a fixed rate depending on species.

3.2.5. Model calibration and testing

Most parameters of the SIMBA model were previously calibrated (Dorel *et al.*, 2008; Tixier *et al.*, 2004, 2006, 2007a, 2008a) and were kept the same for this study. The parameters of the new components of the SIMBA model were calibrated using data issued from the literature and from unpublished experimental trials. Cover crops *B. decumbens*, *Impatiens* sp., and *C. ensiformis* were calibrated by fitting to field trials with data from Achard (pers. com.), Dorel (pers. com.), and Tournebize (pers. com.), respectively. New cultivar types were calibrated to have development, growth, yield, and resistance to pest according to hybrids currently under development (Tixier *et al.*, 2008b). Types 1 and 2 have partial resistance to *M. musicola* and *M. fijiensis,* are sufficiently tolerant to the nematode *R. similis* to stop fungicide and nematicide, have a bunch weight reduced by 30% and 20% respectively, and have a planting-harvest interval reduced by 40% and 20%, respectively.

In addition to the module-by-module validation performed previously (Dorel *et al.*, 2008; Tixier *et al.*, 2004; Tixier *et al.*, 2006) and to the broad yield validation already performed (Tixier *et al.*, 2008a), a new evaluation of the SIMBA model was carried out on the yield for the farm types defined in this study. For this, the measured yields for the six types of farms described in **Table 1** were compared to the yields simulated with SIMBA using a set of inputs (sets of decision rules, soil, and climate parameters) representative of each farm type. There is a significant linear correlation between the measured and simulated yield for the six farm types (r^2=0.93; p-value=0.003; **Figure 1**).

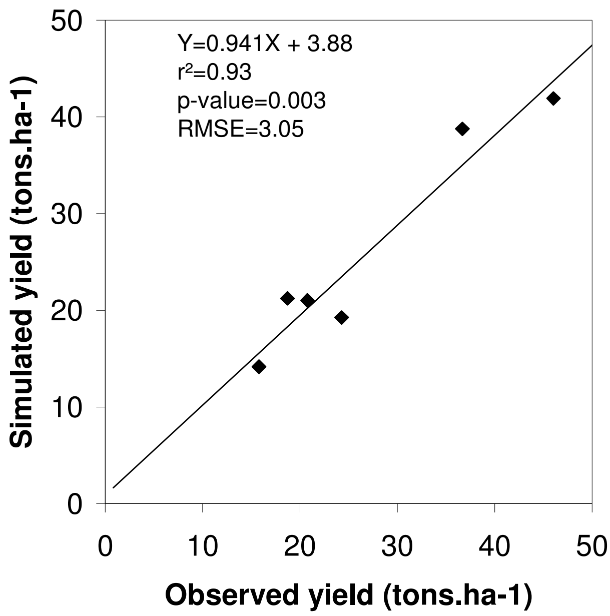

Figure 1. Relation between yield simulated with the SIMBA model and observations in the six farm types.

The equation of the linear correlation shows a slight overestimation of the yield by the model (intercept at 3.88 tons.ha^{-1}), while the slope is almost one (0.94). The root mean square error (RMSE) is 3.05 tons, which is what can be expected for a crop model in comparison with the average yields, between 15.6 and 46 tons.ha^{-1} depending on farm type (**Table 1**). We therefore consider the model as valid for the current practices over the wide range of soils, climates, and technical contexts covered by the 6 farms types. Such validation was not possible for innovations such as intercropping, rotations, or new cultivar because farmers do not apply these innovations yet in all farming situations. However, according to technical experts in contact with some farmers that have tried some or part of innovations considered herein (banana in rotation with *B. decumbens*, intercropping with *C. ensiformis* after fallow, and nematicides' treatments stopping), model results were consistent with their knowledge of the farming situations. Furthermore, in the case of new cultivars, their phenology and their relation with plant-parasitic nematodes were validated (Tixier *et al.*, 2008b) and the effect of rotations was already presented in the case of rotations with fallows (Tixier *et al.*, 2008a).

3.2.6. Evaluation of innovative cropping systems

To assess all the innovations in every context provided by the 6 farm type, we followed a three-step procedure:

- Initializing the model's inputs for each farm type, as described in **Table 2**. These inputs include the soil, climate, and slope characteristics of the field to be simulated.
- Initializing the model's inputs parameters for each farm type, as described in **Table 1**. This includes the decision rules that describe the banana management systems, according to a conditional 'if-then-else' formalism (Tixier *et al.*, 2008a).
- Overwriting the technical decision rules parameters by the ones that describe the technical innovation to be tested. Some innovations can interact indirectly on other components of the system to build a global new consistent management system, e.g., adopting intercropping deactivates herbicide treatments and adopting rotation or improved fallow deactivates nematicide treatments during the 3 years following banana plantation.

This three-step procedure makes it possible to conduct an *ex-ante* 'Farm type × Technical innovation' assessment and can be used to pinpoint technical innovations that could be later on tested in the field.

We did not take into account the inter-annual variation of climate, but we used for each farm type a climate dataset representative of a mean year, with intra-annual variations of climate at weekly step. These climates were obtained by defining an average climate through ten years of data collected from the agro-ecological network of meteorological stations 'RAINETTE' (RAINETTE, 2008). The yield and the amount of pesticide active ingredient used were stored at every time step of the simulations in an output-database. In the final analysis, the yield and the amount of pesticide active ingredient used were summed over the cropping period in order to have a single value for these two variables.

We evaluated the 16 innovations presented in **Table 3** in the context of the six farm types and in comparison with the current ones.

3.3. Results and discussion

3.3.1. Impact of innovations on yield for different farm types

Table 4 shows for a given farm type, the variation between the yield of innovations compared to the yield of the current cropping system, i.e. the ratio ((Yield with innovation Yield of current cropping system) / Yield of current cropping system), expressed in percent. Yield gain of innovative systems varied between -68% and 124% of the yield compared to the current cropping systems. The biggest yield reductions were observed for new cultivars because of their smaller bunch size. Yield increased more i) for rotations and for the integrated systems, except for the one using new cultivars, in the case of farm type 1 and 2 because of the significant reduction of nematode populations, and ii) for intercropping with *C. ensiformis* in the case of extensive systems because of the additional nitrogen provided by the legume plant. In all farm types, some innovations increased the yield while others decreased it. Some innovations were characterized by a relative constant effect on the yield independently of the farm type, e.g. innovations A1, A2, A3, C2, C3, D1, D2, E1, and E2 had a standard error, across farm types, between 0% and 5%. In contrast, all other innovations had a standard error between 18% and 42%. Thus, we can define two kinds of innovations: those having a similar effect on the yield, independently of the farm type and those with a wider range of effect on the yield according to the farm type.

Innovation	Farm type						Mean value	Standard error
	1	2	3	4	5	6		
A1	-1%	-2%	-2%	-1%	0%	-1%	-1%	1%
A2	0%	0%	1%	0%	0%	0%	0%	0%
A3	-1%	-2%	-1%	-1%	0%	-1%	-1%	1%
B1	**73%**	**65%**	**9%**	**16%**	**21%**	**13%**	33%	29%
B2	**56%**	**46%**	0%	3%	11%	4%	20%	24%
B3	40%	38%	-12%	-3%	6%	-1%	11%	22%
C1	25%	34%	**12%**	**16%**	**124%**	**42%**	42%	42%
C2	-6%	-3%	-3%	-4%	1%	-1%	-3%	3%
C3	0%	0%	**1%**	0%	0%	0%	0%	1%
D1	-1%	-2%	-2%	-1%	0%	-1%	-1%	-1%
D2	0%	0%	1%	0%	0%	0%	0%	0%
E1	-64%	-63%	-68%	-67%	-56%	-63%	-64%	4%
E2	-41%	-43%	-46%	-44%	-33%	-40%	-41%	5%
F1	**55%**	**51%**	-2%	**6%**	**18%**	**8%**	23%	24%
F2	**55%**	45%	-1%	2%	11%	3%	19%	24%
F3	-13%	-6%	-44%	-45%	-9%	-35%	-25%	18%

Table 4. Impact of innovations on yield at field level compared to the standard cropping system for all farm types. For each farm type, the three best innovations are in bold.

To illustrate these two types of innovations, we show in **Figure 2** the evolution of the simulated yield of innovations C1, C2, and E2 compared to the yield measured in current cropping systems. Innovation C1 (intercropping with *C. ensiformis*) had an effect on the yield that varied from 12% to 124% across the 6 farm types, while innovations C2 and E2 had an effect from -6% to 1% and from -68% to -56%, respectively. In the case of innovation C1, there was a non-significant negative correlation between the simulated yield gain and the yield in current cropping systems (r^2=0.43; p-value=0.160). Even if it is non-significant, we hypothesize that the gain in yield is bigger when the yield of the current farm type is low, as observed in other studied on crop management systems prototyping (Lançon *et al.*, 2007). Stopping nematicide treatments would induce just few yield reductions (**Table 4**). Probably because farm types 3 and 4 already practice fallow and would not need to use such nematicide whereas those that do not practice any rotation apply too few nematicide for being effective in controlling nematode pressure (farm types 1 and 2).

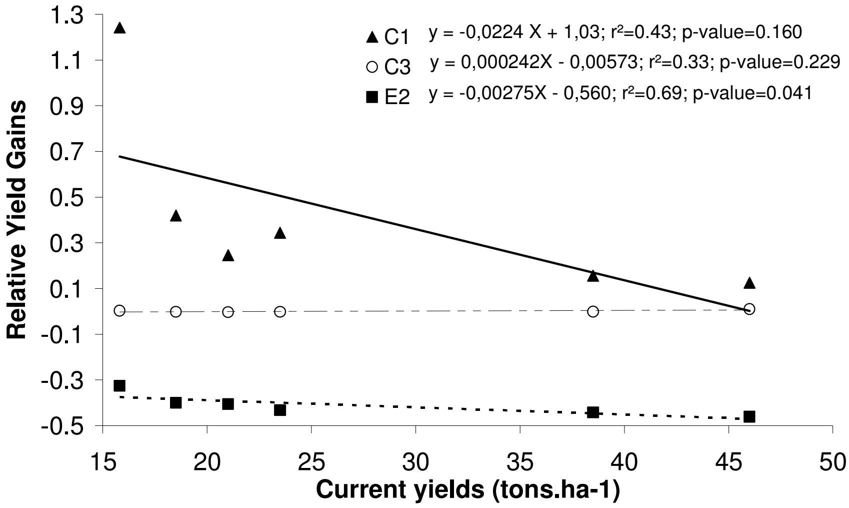

Figure 2. Evolution of the simulated yields gains of innovations C1, C2, and E2 compared to the yields of the current cropping systems.

Innovation	Farm type 1	2	3	4	5	6	Mean value	Standard error
A1	-21%	-27%	-40%	-17%	0%	-46%	-25%	17%
A2	-31%	-30%	-23%	-34%	0%	-54%	-29%	17%
A3	-51%	-57%	-63%	-52%	0%	**-100%**	-54%	32%
B1	-23%	-21%	-14%	-2%	0%	-21%	-13%	10%
B2	-27%	-25%	-19%	-7%	0%	-24%	-17%	11%
B3	-37%	-34%	-30%	-18%	0%	-32%	-25%	14%
C1	-31%	-30%	-23%	-34%	0%	-54%	-29%	17%
C2	-31%	-30%	-23%	-34%	0%	-54%	-29%	17%
C3	-31%	-30%	-23%	-34%	0%	-54%	-29%	17%
D1	-21%	-27%	-40%	-17%	0%	-46%	-25%	17%
D2	-28%	-28%	-21%	-32%	0%	-51%	-27%	16%
E1	**-69%**	**-70%**	**-77%**	**-66%**	0%	-21%	-51%	32%
E2	**-69%**	**-70%**	**-77%**	**-66%**	0%	-21%	-51%	32%
F1	-58%	-63%	-62%	-51%	0%	**-100%**	-56%	32%
F2	-59%	-64%	-63%	-52%	0%	**-100%**	-56%	32%
F3	**-100%**	**-100%**	**-100%**	**-100%**	0%	**-100%**	-83%	41%

Table 5. Impact of innovations on pesticide uses at field level compared to the standard cropping system for all farm types. For each farm type, the three best innovations are in bold.

3.3.2. Impact of innovations on the pesticide uses for different farm types

We then evaluated the pesticide use for the 16 innovations in the context of the six farm types. **Table 5** shows the variation between the pesticide use in innovations compared to the pesticide uses in the current cropping system, i.e. the ratio ((Pesticide use of innovation Pesticide use of current cropping system) / Pesticide use of current cropping system), expressed in percent. In this analysis we do not consider farm type 5, where the current cropping system is very extensive and already does not use pesticides. Reduction of pesticide use in innovations varied between -100% (total suppression) and -2% of the amount of pesticides used in the current cropping systems. Innovation A3 (stopping nematicides and herbicides), E1 and E2 (resistant hybrids) and integrated innovations F1 and F2 led to a strong reduction in pesticide uses, over 50%. Innovation F3 (integrated system with resistant hybrids) allows a complete stopping of pesticide uses.

3.3.3. Most promising innovation for each farm type and tradeoffs between yields and pesticide reduction

To identify the most promising innovations for each farm type, we identified three sets of constraints imposed by the farm context (Lançon et al., 2007) and which define the threshold of the impacts of innovations on yields and on pesticide uses to accept or reject this innovation for this farm type.

For farm type 1 and 2 that have low yields and a high level of pesticide uses, we chose to select innovation pairs that lead to a minimum increase in yield of 25% while decreasing the use of pesticides by at least 25%. For farm types 3 and 4 that show high yields and pesticide use levels, we chose to retain those innovations that lead to a minimum decrease of 25% in pesticide uses while keeping at least 95% of current yields. The 5%-yield losses were considered acceptable for these types because they already have high yield and the savings on inputs can compensate this possible loss. For farm types 5 and 6 that have low yields and pesticide use levels, we considered as promising innovations those that lead to an increase of at least 20% in the current yields without increasing the use of pesticides. Summary and results of this procedure are presented in **Figure 3** and **Table 6**. For each farm type the most promising innovations are located on the right of the vertical line and below the horizontal line in **Figure 3,** into dotted rectangle**.**

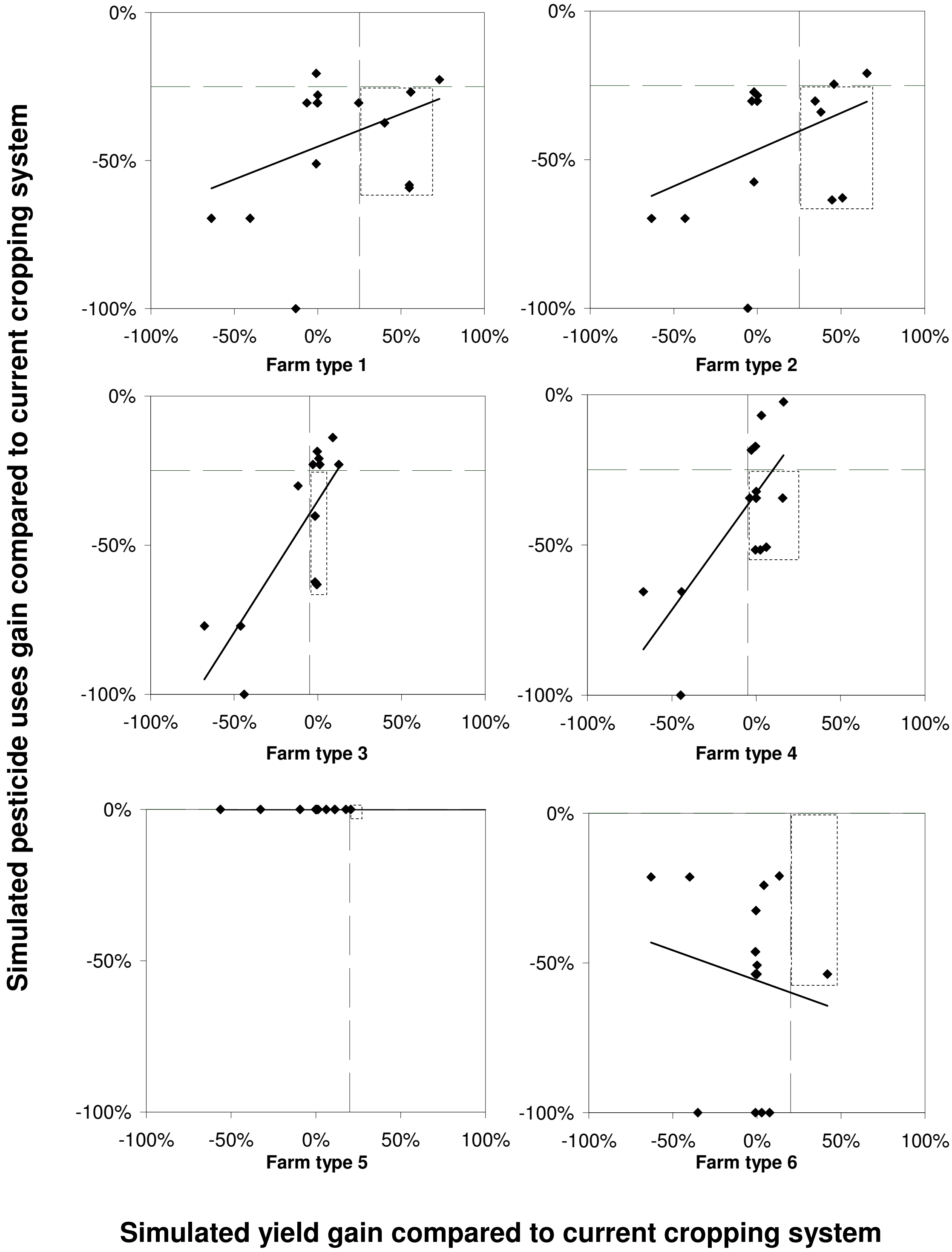

Figure 3. Impacts of innovations on pesticide uses and yields for each farm type.

Promising innovations according to thresholds defined in table 6 are included in dotted rectangles.

The number of innovations that match the criteria established varied from only one for farm type 6 up to eight innovations for farm type 4, showing that the scope for innovating can vary considerably across farm types. Most of promising for farm types 1 and 2 include rotations (B2, B3, F1 and F2). For farm types 1 and 2, rotations are the key practice to be incorporated into their crop management sytems to control nematode pressure and thus allowing to reduce pesticide uses and increase yields. The innovation C1 (intercrop with *C. ensiformis*) is also interesting for farm type 2 because it uses a low level of nitrogen fertilizers and benefits more from increased nitrogen input provided by this legume cover crop.

Farm type	Yields' impacts threshold	Pesticide uses' impacts threshold	Matching innovations	Equation of the linear regression	r^2	p-value
1	25%	-25%	B2 B3 F1 F2	y = 0.453 + 0.220 x	0.13	0.171
2	25%	-25%	B3 C1 F1 F2	y = 0.466 + 0.246 x	0.14	0.158
3	-5%	-25%	A1 A3 D1 F1 F2	y = 0.351 + 0.884 x	0.56	0.001
4	-5%	-25%	A2 A3 C1 C2 C3 D2 F1 F2	y = 0.327 + 0.779 x	0.52	0.002
5	20%	0%	B1 C1	*not performed*	-	-
6	20%	0%	C1	y = 0.558 0.201 x	0.02	0.550

Table 6. Yields and pesticide uses thresholds for selecting promising innovations, matching innovations and regression between the effect of innovations on the yield (x) and the effect of innovations on the pesticide uses (y) for each farm type.

Innovations that consist in reasoning or stopping pesticide uses (innovation from type A and D in **table 3**) are promising for farm types 3 and 4. For type 3, this could be because nematicide uses is not necessary since they already use crop rotations. It is interesting to observe that, although rotations and intercroppings do not satisfy individually the set of constraint, they do satisfy it when combined into integrated systems (e.g. for farm type 2, B2 and C3 do not satisfy the set of constraints but F2 do). This shows that, for some situations, sustainable systems can only be achieved by combining different technological innovations. Compared to farm type 3, farm type 4 shows a larger scope for innovation since all kind of intercropping seem promising technologies for this farm type. The environmental characteristics of farm type 4, with deeper soils and a higher rainfall could represent ideal conditions for the cultivation of the tested cover crops.

For farm types 5 and 6 the most promising innovations are those that improve nitrogen nutrition through the use of legume crops either with rotation or with intercropping (B1 and C1) for farm type 5 and only with intercropping for farm type 6.

It is interesting to pinpoint that innovations based on the use of disease resistant cultivars (E1 and E2) were not selected as promising innovations for none of the farm types mainly because of decreased yields. Breeders will have to focus on the bunch size as an important criterion before disseminating these varieties as innovations. Integrated systems (innovations F1, F2, and F3) are the most efficient ways to reduce pesticides, with mean values of 56%, 56%, and 83%, respectively.

Then we sought to determine whether there was a trade-off between pesticide reduction and yield variation for each farm type separately (see regression curves of these two variables on **Figure 3** and equations in **Table 6)**. There is a significant positive correlation for farm types 3 and 4, which are the two most productive ones (slopes of 0.884 and 0.779, respectively). This result shows that the more productive the farm, the higher the decrease in yield caused by 'environmentally friendly innovations'.

These findings support the hypothesis that some innovations are more efficient (increase in yield and reduced pesticide use) for some farm types. Nevertheless, the number of promising pairs of innovation-farm type is small (24) compared to the total number of pairs evaluated in our study (96). This reinforces the need for exploring a wide range of innovations in order to increase the probability of fitting with the specific context of each farm type and hence increase the likelihood of adoption. Furthermore, for a single type of innovation (e.g. intercropping or improved fallow), one variant can be promising in a farm type while another is not, and inversely in another farm type (e.g. B1 is promising for farm type 5 and B3 is not promising, wich is the opposite for farm type 2). Finally, the results show that, despite an apparent trade-off between yield and pesticide uses, there are some innovations that can address both production and the environmental issues.

3.4.Limits and perspectives

The main limit of our results lies in the validity of the model, within the innovation-soil-climate-technical context range explored in this study. Although there is a good precision for the yield of current cropping systems (**Figure 1**), it is difficult to validate the simulation of innovations in farming contexts where these innovations have never been tested. This issue underlines the difficulty for researchers to know how much they can trust models when they are testing innovations in the specific context of a farm. A more extensive evaluation of the model is therefore needed before using these types of results to disseminate innovations. But this does not reduce the value of the methodology proposed in this study using the SIMBA model. This model was especially designed for the banana-based systems; it thus efficiently accounts for the specificities of the banana crop e.g. unsynchronized plant population, but also the specificities of the management of the system by the farmer. Hence, it appears to be well adapted to the assessment of technologies contextualized in the biophysical and the technical parameters of a given farming situation. The cropping system functioning includes interactions between biophysical processes and technical actions; it is thus impossible to assess one technical part of the system independently of others. Biophysical models allow systemic assessment of technical innovations accounting for the technique-technique and technique-biophysical interactions.

Our simulations allowed us to identify, for different farm types, the innovations that increase yield while reducing pesticide. However, the work has to be completed by a cost-benefit analysis of the alternative systems relative to the current ones (Nelson *et al.*, 1998). For instance, fallows adoption increases yield but requires a transition period (fields are not productive during the fallow) that is critical for low-resource farmers. Economic assessment of yield benefits due to innovations should also include the cost of labor, land and inputs, over the whole crop succession (Swinkels *et al.*, 1997). The cost of additional labor for innovation is particularly important for intercropping systems that replace pesticides by labor. This additional cost may be a major issue in farming contexts of high-cost labor (Thangata and Alavalapati, 2003), as in F.W.I. Innovation is a complex process that depends on many determinants relative to farmers' socio-economic characteristics and innovations' attributes (Abadi Ghadim and Pannell, 1999). Climatic and economic risks associated with the adoption of an innovation also have to be assessed (Marra *et al.*, 2003). To this end, *ex ante* studies aimed at identifying farmers' constraints to the adoption of innovations should be performed using both farm surveys and on farm trials.

3.5. Conclusion

The simulation of innovative cropping systems with the SIMBA model demonstrates the importance of farm type in assessing yield and pesticide uses for cropping systems based on low input innovations. Some innovations in some specific farm contexts led to a benefit both for production and for environmental issues. These innovations are mainly rotation or improved fallows, intercropping, and integrated systems. Even though resistant cultivars allow to reduce considerably pesticide uses, field performances were radically altered by lower yield potential. This study showed that farmers have different room for manoeuvre for innovating as the number of promising innovation vary considerably among farm types, according to their biophysical and technical current situations. The study of the 'farm type by farm type' trade-off between yield gains and pesticide reduction showed that environmentally friendly innovations cause more yield decreases in the more productive farm types. Our modeling study confirms the importance of the innovation-farm type interactions mentioned by other authors (Lançon *et al.*, 2007) and the usefulness of models for assessing a large number of technological innovations among a wide range of biophysical and technical situations.

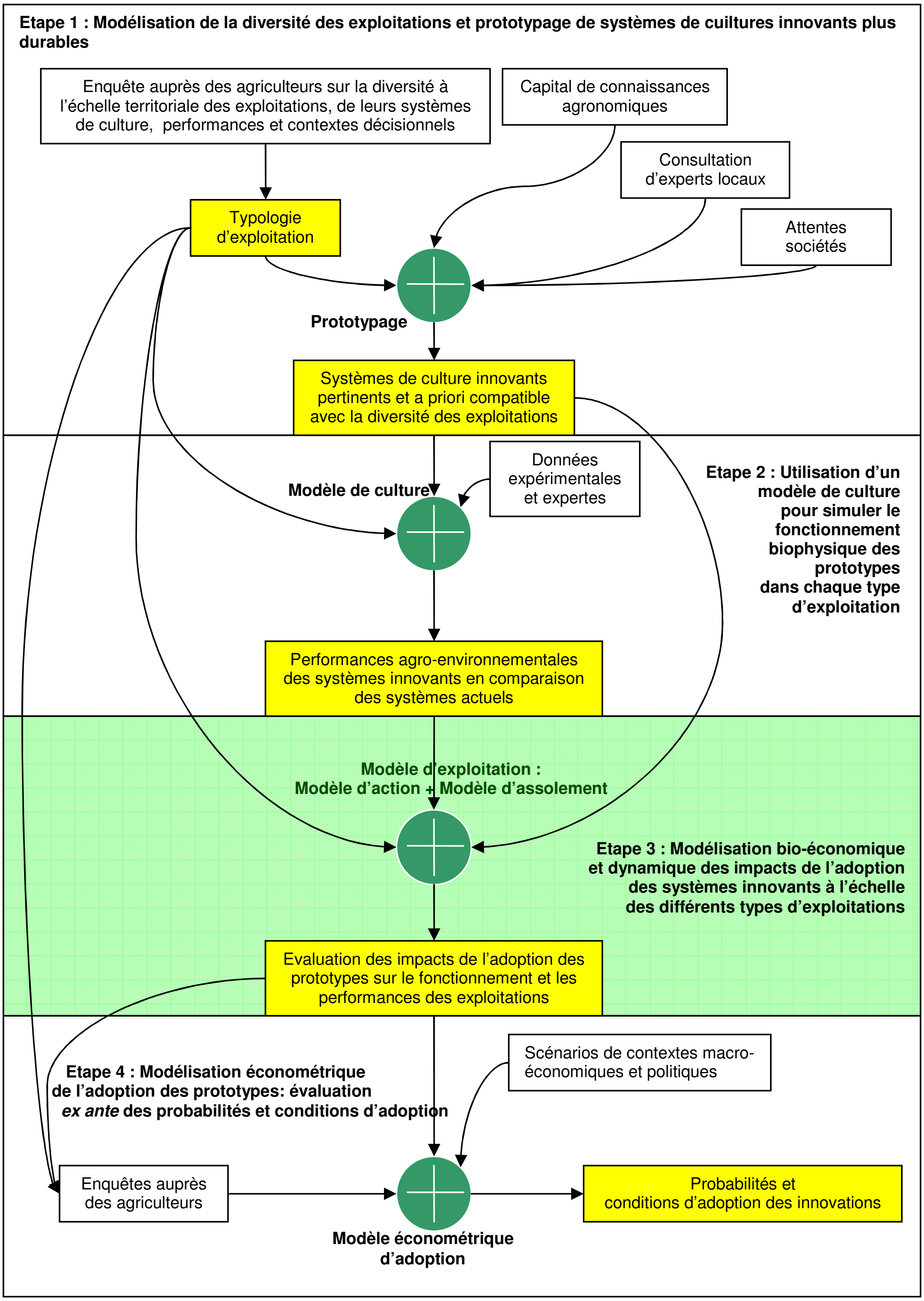

Figure 2 : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

4. Modélisation bio-économique et évaluation des impacts de l’adoption des prototypes sur le fonctionnement et les performances des exploitations

Ce chapitre correspond à la description de la troisième étape de la méthode (cf. figure C). Cette étape a pour objectif d’évaluer les impacts de l’adoption des prototypes de systèmes de culture innovant sur les différents types d’exploitation. Les processus simulés par le modèle sont la production de l’exploitaion, l’usage de pesticides, le travail et le revenu cumulé (flux de trésorerie), à différents pas de temps allant de la semaine à la dizaine d’années. Il s’appuie donc sur des résultats issus des deux premières étapes.
A cette fin, nous avons construit un modèle bio-économique d’exploitation: BANAD (pour **B**io-economic farm model for **A**ssessment of impacts of i**N**novation **AD**option at farm level). Le modèle a été est évalué et paramétré afin d’évaluer les impacts de toutes les prototypes de systèmes de culture innovants dans toutes les exploitations.

Cette troisième étape de la démarche globale est présentée dans l’article suivant, intitulé « **BANAD: a dynamic bio-economic farm model for ex ante assessment of the impacts of innovation adoption. Application to banana systems in Guadeloupe** », qui a été soumis à la revue ***Agricultural Systems*** (http://ees.elsevier.com/agsy/).

Cet article décrit d’abord la structure du modèle et les formalismes de modélisation utilisés, puis présente de manière détaillée les résultats de l’évaluation des impacts de l’adoption de 7 prototypes de systèmes de culture innovants (les prototypes B1, B2, B3, C1, E2 et F3) pour 3 types d’exploitation. Dans cet article les types d’exploitation A, B, et C correspondent respectivement aux types 1, 3 et 5 des deux chapitres précédents. Nous avons choisi d’illustrer les résultats avec ces 3 types d’exploitation et ces 7 prototypes car ils représentent toute la gamme de systèmes de cultures actuels et innovants, et de contextes biophysique et socio-économique.

BANAD: a dynamic bio-economic farm model for ex ante assessment of the impacts of innovation adoption. Application to banana systems in Guadeloupe.

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Abstract

Ex ante assessment of innovative crop management systems is a key step in the development of more sustainable systems. To this end models are useful tools because they make it possible to assess rapidly numerous innovations in different contexts. Whereas many farm models focus on the farmer's strategic decision of adoption, few modeling studies consider the dynamic operational impacts of innovation adoption on its performances and functioning at farm scale. BANAD, a mechanistic model for such applications is proposed. It includes four components i) a farm typology database, ii) a crop model (SIMBA), iii) a crop management system model, and iv) a farm level integration model. The paper first presents the generic structure of the model and the mathematical formalisms used to model the biophysical and socio-economic processes at farm level during the innovation adoption process. Then are presented the results of the model applied to the ex ante assessment of six innovative banana management systems for three contrasted farm types in Guadeloupe. Our results showed that the impacts of innovations, which includes rotations, improved fallow, intercropping, hybrid cultivar, and an organic system, can vary considerably among farm types for a given innovation and among innovations for a given farm type. Innovative cropping systems that were effective at field scale in terms of yield improvement and pesticide use decrease could be problematic at farm scale because they decreased income and increased workload. Adoption of rotations or improved fallow seemed to be relevant for smallholders but could induce a critical period of 1.5 to 2.5 years during which income decreased drastically. Under certain conditions of markets and subsidies very environmentally friendly innovations that are less productive can be economically effective. The paper finally proposes some recommendations to prototyping scientists and policy makers in order to improve the likelihood of adoption and discusses the limits and the genericity of the structure and the formalisms of the BANAD model.

Keywords : bio-economic farm model, ex ante assessment, innovation, adoption, intercropping, rotation, hybrid, organic system, Musa spp, Caribbean.

4.1. Introduction

Climate change, societal demand for cleaner and safe production, and market fluctuations act on agricultural systems as driving forces and make them irrelevant or unfit for these new conditions (Hatfield et al., 2007). Adopting technological innovation is a key point for farmers to maintain the economic sustainability of their farm while conforming to environmental regulations. In this perspective agronomists have to innovate with technology. To this end, a key step is the ex ante assessment of the possible impacts of innovations at farm scale (van Ittersum et al., 2008). Models are increasingly used to design and evaluate innovative agricultural systems because they enable ex ante assessment of innovations in limited time and on a large range of situations.

Most models used in published studies run at field level and thus allow only a partial assessment of innovations from an end user's point of view. Most of the impact assessments at farm level are made through experimental (participatory or not) on farm trials, which are costly and long to implement, and are generally implemented on a single part of the farm (Vereijken, 1997). Many bio-economic farm models have been published, but they are mostly aimed at assessing farmer's responses to the introduction of an innovation in terms of land allocation between several activities, given their economic attributes, with linear programming models (Janssen and Van Ittersum, 2007). Most of these studies focused on the strategic decision making, and their aim was to model innovation adoption in terms of adoption rates, hence restricting innovation adoption to its economic dimension. In these models, the farm is described in a static way and with a limited consideration of farm diversity. This makes farm models difficult to use in prototyping approaches (Sterk et al., 2006; 2007). Even though these models are useful to assess policy interventions, they are not appropriate to assess the various impacts that innovation adoption can have on the performances and on the functioning of farms in terms of workload, income, pesticides, and agricultural production. These four criteria, however, are key components of sustainability and of farmers' decision making for deciding to adopt or not an innovation. It is thus necessary to take them into account in the design of any innovation (Gafsi et al., 2006). Bio-economic modeling of agricultural systems is faced with two challenges: How to simulate the operational and dynamic impacts of innovation adoption at farm level? And how to be generic enough to take into account farm diversity in this analysis?

This paper proposes a bio-economic farm model (BANAD) aimed at answering such questions. It is aimed at assessing the dynamic impacts of innovation adoption at farm scale in terms of production, workload, net income, and pesticide use, while taking into account farm diversity at regional level. We used the BANAD model to answer several assessment issues for defining agronomic and policy recommendations, in order to increase the likelihood of adoption of technological innovations: (i) assessing the dynamics and multiple impacts of adopting an innovation at farm scale, (ii) comparing the impacts of different innovations in a farm type, (iii) assessing the sensitivity of farm level criteria to innovation parameters, (iv) comparing a given innovation among several farm types.

The model has been developed on banana farms in Guadeloupe to assess several low input innovations involving improved fallow, intercropping techniques, new hybrid cultivars, and integrated systems. As a response to the severe economic and environmental crisis banana production is facing in Guadeloupe, these innovations are under development on experimental stations and the aim of the study was to assess them on virtual farms representative of the major types of commercial farms. We first present an overview of the farm model and then detail its components and the method to parameterize and evaluate it. Then we present the results of the application of the model to the assessment of seven innovative systems on three farm types and at different time scales. Finally, we formulate some agronomic and policy recommendations for banana systems in Guadeloupe and discuss the effectiveness and the limits of the model.

4.2. The model

4.2.1. Overview

BANAD is a bio-economic farm model simulating jointly the biophysical and technico-economic processes at farm level under different scenarios of farm context and innovation adoption. It is a mechanistic model based on available theory and knowledge of farm processes. BANAD is a dynamic model that runs at a weekly time step and at farm scale, the farm being represented as a system of production processes under the control of farmer's tactical and strategic technical decisions. In this model, the strategic decision of adopting an innovation is forced by the model's user. Tactical decisions related to daily action are modeled with a set of decision rules. BANAD is a normative model in which the norm is the implementation of this set of decision rules. These rules result from the systemic integration of one or several innovations into current observed practices that are adapted according to the nature of these innovations.

In the case of banana farms that are specialized in banana production for export, the farm can be represented by a set of semi-perennial asynchronous banana fields producing banana bunches that are weekly harvested and packaged in a conditioning facility for export. Production inputs include chemical products (herbicides, nematicides, insecticides, fungicides, fertilizers) and packing materials. The model simulates weekly the actions in the various types of fields and in the conditioning facility and computes flows and uses of farm production factors, such as money, land, work, inputs.

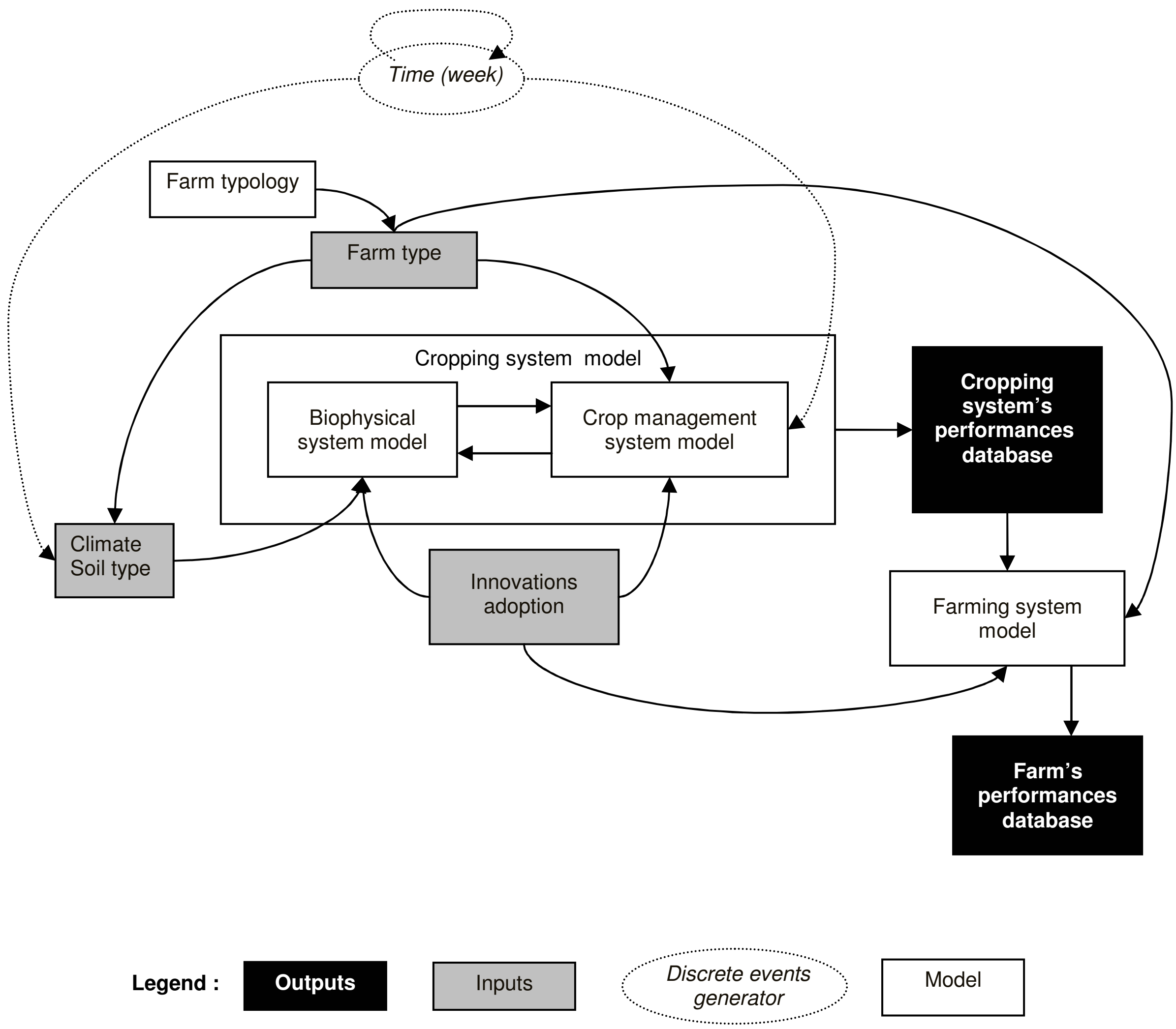


Figure 1. General structure of the Bio-economic farm model for Assessment of impacts of iNnovations ADoption at farm level (BANAD).

Figure 1 gives an overview of the general structure of the model. The model allows one to simulate farm functioning for adoption of various technical innovations chosen by the model's user for each farm type. Outputs of the model are dynamic at a weekly time step and relative to banana production, cash flow level, workload, and environmental impacts indicated with the amount of pesticide active ingredient used. The model allows one to compare current and innovative crop management systems (CMS) for the various farm types in a region. The inputs of the model are a set of parameters relative to i) decision rule parameters of the banana management system; ii) soil and climate conditions; iii) farm characteristics; and iv) market prices and public subsidies related to a policy. The values of these parameters depend on farm type and on the nature of the innovative techniques, once they are adopted.

The model is made of four components:

- a farm database to model the diversity of physical, socio-economic and technical farm context at regional level,
- following the representation of Rapidel et al. (2007), a cropping system model that runs at field level is represented as a biophysical crop model in interaction with a model of crop management system (CMS):
  - the crop model (called SIMBA, Tixier et al., 2008a) simulates biophysical processes such as banana growth and pest development and impacts and all the techniques that have an impact on these processes,
  - the CMS model simulates all the cultural practices on the field during each week,
- a farming system model that combines and integrates performances from several fields over time.

The dynamics of farm functioning are modeled with an internal "clock" that generates discrete events at a weekly step, which are course of time and weekly climatic characteristics (temperature, rainfall, and solar radiation).

4.2.2. Farm types

The model was used for three farm types (Table 1) representative of the diversity of farming situations in Guadeloupe, previously described by a farm typology (Blazy et al, 2008). Type A is a small farm (4.2 ha) in the lowlands, with mainly familial, abundant, and low cost manpower. It is a banana monocrop farm with replanting every five years. This system is medium intensive with one nematicide treatment, five herbicide treatments, and 12 nitrogen applications per year.

Category	Characteristics	Units	TYPE A	TYPE B	TYPE C
Farm production factors	Farm acreage	ha	4.2	82.0	8.0
	Mean cost of manpower	€ d^{-1}	32.6	61.1	40.8
	Work resources	$d.ha^{-1}yr^{-1}$	178.6	136.5	104.7
Environmental conditions	Mean annual rainfall	$mm.yr^{-1}$	2614	2700	4118
	Mean sunlight	$MJ.m^{-2}.d^{-1}$	18.1	17.5	17.3
	Soil type	-	Nitisol	Nitisol	Andisol
	Mean slope	%	10%	10%	20%
	Mean altitude	m	80	123	550
Crop management system	Fallow duration	week	0.0	52.0	0.0
	Delay before replanting	year	5.0	5.0	10.0
	Nitrogen applied per plant per application	kg pl^{-1}	15	15	30
	Number of nitrogen applications per year	yr^{-1}	12	17	3
	Number of herbicide treatments per year	yr^{-1}	5	5	0
	Number of nematicide treatments per year	yr^{-1}	1	4	0
	Type of destruction of banana fields before replanting	-	mechanical	mechanical	manual
	Type of tillage at plantation	-	mechanical	mechanical	manual
Farm performances	Amount of active ingredient of pesticide applied per year	kg ha^{-1}	27	30	0
	Average banana production at farm level	$10^{\wedge 3}$ kg ha^{-1} yr^{-1}	21	33	16
	Net income indicator (provided by farmer)	-	little income	suitable income	deficit

Table 1. Characteristics of the three types of farm simulated in this study.

Productivity is relatively low (21 t ha-1) and income level as well ("little income"). Type B is a big farm (82 ha) with mainly full-time permanent employees. Banana is rotated every 5 years with a 12-month fallow. It is a relatively intensive system with four nematicide treatments and five herbicide treatments each year. Agronomic and economic performances are good (33 t ha-1 year-1; "suitable income"). Type A and B are in the lowlands with no slope and with sometimes limited rainfall. However, only type B has access to irrigation. Type C is in the uplands at 550 m altitude, with steep slopes and abundant rainfall. It is on andisol and practices perennial management of banana. This farm type is very extensive with no use of nematicide or herbicide, and only 3 applications of nitrogen per year. Its workforce is limited, average yields are low, and economic results are negative.

4.2.3. Innovations

The model was initially developed to assess 16 innovations involving adoption of rotations or improved fallow, intercropping, new hybrid pest-resistant cultivars, regulation of pesticide use, and integrated systems. In this paper we present only the results of the assessment at farm scale of six contrasted innovations that have been tested on the three farm types. These six innovations were:

- Three types of rotations that are aimed at durably regulating nematode populations: 12-month fallow chemically controlled, 8-months fallow with *Crotalaria juncea*, and 24-month rotation with pineapple. We considered that these rotations should be associated with an absence of nematicide treatments during three years. These rotations involve additional operations for plowing, sowing, and/or managing the rotation crop. Pineapple is a cash crop but the rotation is long (24 months) and it requires costly management. Chemically controlled fallow is shorter (12 months) and needs little labor but is unproductive. *Crotalaria juncea* is a legume crop that can provide about 50 kg ha-1 year-1of nitrogen to soil before banana plantation, and it provides efficient control of nematode pressure (Thammaiah et al., 2007).
- Intercropping banana with a legume cover crop, *Canavalia ensiformis*. This species is appropriate for banana intercropping as it can limit weed development and provide nitrogen to soil without increasing pest populations (McIntyre et al., 2001). This is an annual cover crop that needs regular replanting and mulching at flowering. However, observations on experimental trials showed that it can increase work duration of other field operations by about 20%.

- A new hybrid cultivar that has partial resistance to *Mycosphaerella musicola* and *Mycosphaerella fijiensis* (Bakry et al., 2007) and is sufficiently tolerant to the nematode *Radopholus similis* to avoid fungicide and nematicide application. Whereas this cultivar is less productive (bunch weight 20% lower than classic Cavendish cultivars), it produces a new kind of banana, which is smaller and with a different taste. Due to these new characteristics, the sale price of this banana was considered to be 50% higher than that of conventional banana.
- An innovative organic banana system combining improved fallow with *Crotalaria juncea*, intercropping with *Canavalia ensiformis*, new hybrid cultivar, and organic fertilization, with no chemical inputs. We considered that, due to its organic nature, the sale price of banana produced by this system would be 100% higher than that of conventional banana, which is close to actual price of organic banana in Europe (Chotard, *personal communication*).

All these innovations have been under development for more than 15 years in the French West Indies. All of them have been studied in multi-year trials, some have been tried on commercial farms. All the model parameters for these innovations were derived from experiments (Ternisien, 1989; Ternisien and Melin, 1989; Mateille et al., 1994; Chabrier and Quénéhervé, 2003; Clermont Dauphin et al., 2004; Quénéhervé et al., 2006; Motisi et al., 2007; Tixier et al., 2008b).

4.2.4. Modelling farmer’s actions

The farmer’s action was modeled by a set of decision rules with decisional variables and threshold parameters (Merot et al., 2008). Each operation is described by a set of 11 parameters, presented in **table 2**. P1, P3, P4, P5, P10, and P11 are decisional variables used to model farmer’s action in the crop management system sub-model and in the biophysical sub-model. P2, P6, and P7 are input parameters of the biophysical sub-model. P9 is used to calculate workload, and P7 and P8 are used in the calculation of net income and pesticide use. In BANAD, the parameters of each operation are determined by the technical nature of the innovation, the farm type selected, the innovation adopted, and other operations’ parameters. **Figure 2** gives an overview of the factors that influence the values of operation parameters.

Variables	Units	Definition
P1: Presence	dummy variable (0 or 1)	equals one if the operation is present in the CMS, zero otherwise
P2: Modality	qualitative variable	technical modality of the operation
P3: Frequency	weeks	interval between two repetitions of operation
P4: Beginning date	week number	date from which operations can take place
P5: End date	week number	date from which operations cannot be done any more
P6: Amount of pesticides	kg ha^{-1}	amount of active ingredient applied
P7: Amount of chemical fertilizers	kg ha^{-1}	amount of chemical fertilizers applied (equivalent 15%N, 4%P, 30%K)
P8: Amount of non chemical inputs	€ ha^{-1}	cost of non chemical inputs used
P9: Operation duration	days ha^{-1} or days $plant^{-1}$	duration of the operation
P10: nb controlling biophysical variable	*	Equal to 0 if operation is not controlled by biophysical variable, otherwise gives the number of controlling biophysical variables concerned
P11: activation threshold	**	Activation's threshold of controlling biophysical variable

* = adimensional
** = unit depends on the nature of the biophysical variable

Table 2. Definition of the parameters used to model each operation of the crop management system (CMS).

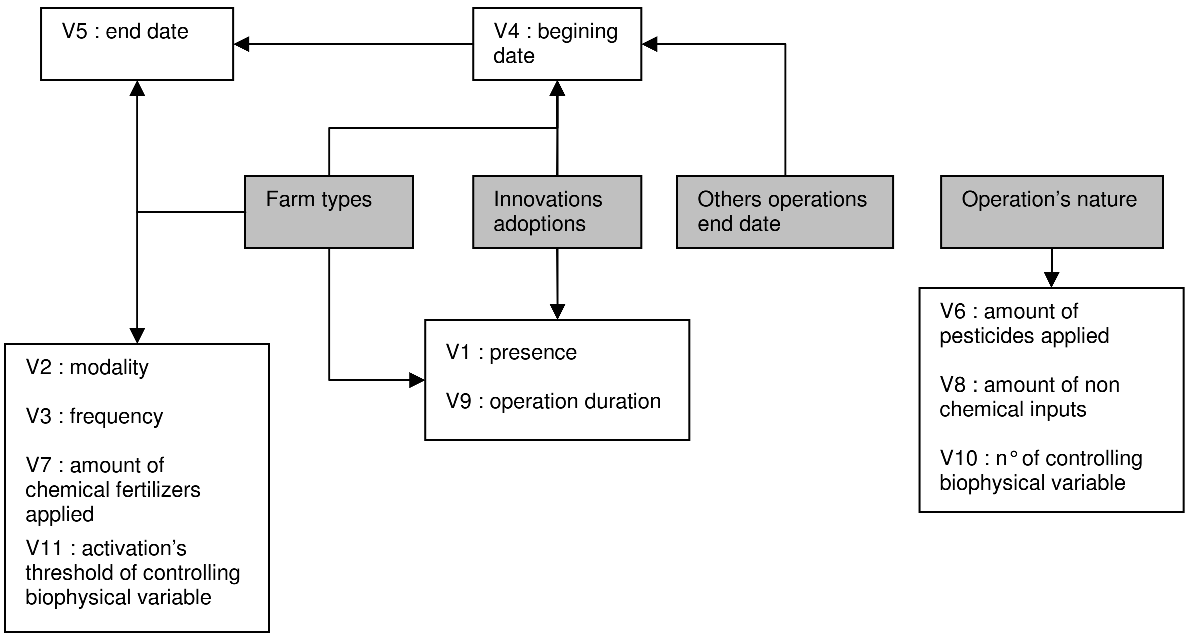


Figure 2. Factors influencing values of operation parameters in the program for automatic adaptation of CMS to farm type and innovation adoption.

The influence of these factors on decisional variables was automatized with “IF <conditionA=TRUE> THEN <action1> ELSE <action2>” decision rules. Examples of condition are “Farm type = C” or “adoption of intercropping =TRUE”. P1 and P9 are influenced by the choice of farm type and by the activation of innovation adoption. P2, P3, P7, and P11 are influenced only by farm type. P4 is influenced by farm type, innovation adoption, and other operations’ end date (e.g. banana planting two weeks after plowing, and plowing when fallow period is over). P5 is influenced by P4 and farm type. P6, P8, and P10 are determined only by the nature of the operation.

The advantage of this generic representation is that it facilitates the model’s parameterization by selecting only a farm type and an innovation. The CMS model automatically designs a whole CMS close to the reality of the farm type and adapted to the innovation adopted.

As an example of this modeling process of a CMS, **Table 3** illustrates how the impacts of adopting two types of innovations modify the parameters of nematicide applications for farm type A.

	Units	**Current**	**Adoption fallow**	**Adoption organic system**
P1: Presence	dummy variable	1	1	0
P2: Modality	qualitative variable	Fosthiazate	Fosthiazate	Fosthiazate
P3: Frequency	weeks	52	52	52
P4: Beginning date	week number	2	210	193
P5: End date	week number	260	312	294
P6: Amount of pesticides	kg ha-1	3.6	3.6	0
P7: Amount of chemical fertilizers	kg ha-1	0	0	0
P8: Amount of non chemical inputs	€ ha-1	0	0	0
P9: Operation duration	days ha-1	0.68	0.68	0.81
P10: nb controlling biophysical variables	*	0	0	0
P11: activation threshold	**	0	0	0

* = adimensional
** = unit depends on the nature of the biophysical variable

Table 3. Values of the 11 operation parameters for operation “Nematicide treatments” for farm type A for the current situation and two innovations.

Adopting a 12-month fallow makes the first application switch from day 2 to 210 because, when adopting a 12-month fallow, the model automatically delays nematicide application by 52 weeks (fallow duration) plus 156 weeks during which nematicide is not required due to the cleansing effect of fallow on nematode population. Adoption of an organic system de-activates nematicide application because of the nature of the innovation, which prohibits all pesticide uses. This case is interesting because it illustrates the effects on the duration of this operation (switch from 0.68 days ha^{-1} to 0.81 days ha^{-1}) because of the intercrop between two rows of banana, which makes all field operations more complex. Once all parameters are set up by the user (choice of farm type and innovation), the automatically adapted CMS is ready for simulation both with the crop model and the CMS model.

4.2.5. Use of the SIMBA model to simulate biophysical processes

The SIMBA crop model (Tixier et al., 2008a) was used in this study to simulate biophysical processes in response to CMS. It runs at field level over several cropping cycles. This model includes sub-modules that simulate soil structure, water balance, root nematode populations (Tixier et al., 2006), and yield, with a sound balance between representing the major processes of the system in the region and keeping the model simple to reduce the parameterization costs in a large range of conditions. It is able to simulate the main specificity of banana crop, that is, the establishment of asynchronous flowering regime, which strongly affects the homogeneity of the plant population structure after several production cycles (Tixier et al., 2004). This specificity is important because it influences work efficiency and the dynamics of banana production and therefore farm functioning. SIMBA makes it possible to account for most of the operations of banana management and for a large set of innovative techniques like rotations, intercropping, new hybrid cultivars, and on a large range of farming situations (Blazy *et al.*, submitted).

The input parameters of this model are soil porosity, slope, depth, and organic content; operations' decision rules; climatic parameters, described at weekly step by cumulated temperatures, solar global radiation, and rainfall; initial parasitic pressure; and soil N mineral content.

We used an average climatic year, representative of each farm type context, and repeated during 10 years, in order to avoid the impact of climate variation on interactions between farm type and innovation, which makes the interpretation of the results easier. However, although this simplification of climate representation (no inter-annual variations) can be justified in the

case of a preliminary assessment of innovation, the sensitivity of innovation impacts to a succession of contrasted climatic seasons should be tested in another study.
Finally SIMBA is well adapted for modeling farming systems as its parameterization is relatively convivial and transparent and its outputs can be automatically compiled in databases, which makes this model easy to link to other models, like bio-economic farm models.

4.2.6. Crop management system model

The CMS is represented by a matrix of **t** rows and **p** columns, the rows being the week number of the simulation and the columns the different possible operations (in our case **p = 48**, and **t** can vary from **260 to 624** depending on farm type and innovation). Then an algorithm calculates elements of the CMS matrix with simple decision rules using matrices of operation parameters and outputs of the biophysical database. This algorithm can be described as follows.
To model a crop management system (CMS) compound of **p** operations $\mathbf{O_j}$, with **b** operations that are conditioned by **b** biophysical variables $\mathbf{B_w}$ and **(p – b)** operations that are conditioned only by time.
Let D be a matrix of **p** rows and 11 columns with $\mathbf{D(j,y)=Py(O_j)}$=value of the $\mathbf{y^{th}}$ parameter of operation $\mathbf{O_j}$ as described in section 2.2 (see table 2 for the definition of these parameters). For example, for operation $\mathbf{O_j}$: $\mathbf{D(j,1)=P1(O_j)}$ (V1 is presence or not of operation Oj in the CMS).
Let **CMS** be the matrix representing the CMS during the total duration of the crop pattern.
CMS is compound of **p** columns and **e** rows, with $\mathbf{e=MAX_{j=1:p}[D(j,5)]}$ (**e** represents the total duration of the crop pattern). **CMS(t,j)=1** if operation $\mathbf{O_j}$ is done on week number **t**, and **CMS(t,j)=0** otherwise.
Let **BCMS** be a matrix of **b** columns and **e** rows, with **BCMS(t,w) =** value of biophysical variable $\mathbf{B_w}$ on week number **t**. Elements of matrix **BCMS** are calculated by the SIMBA model.
Let **wuo** be an auxiliary variable used in the algorithm to model the “amount of remaining weeks until operation is done” which is thus decreased each week from one unity until it becomes equal to one, which activates the operation. This variable is not used in the modeling of operations, which depends on the states of the biophysical variables.
Once all these matrices have been created, the simple algorithm presented in **figure 3** makes it possible to calculate elements of matrix **CMS**.

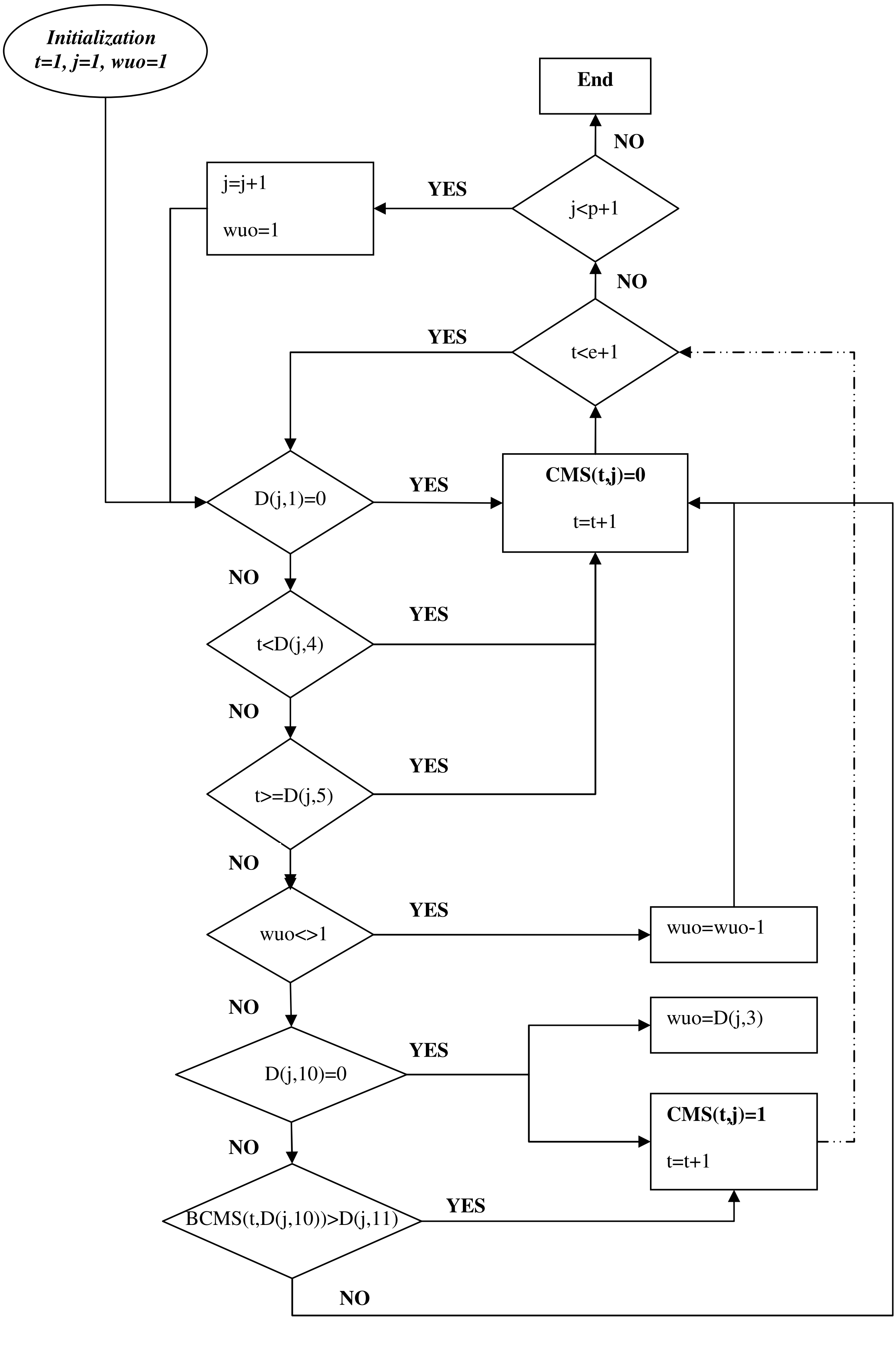


Figure 3. Algorithm for calculation of crop management system (CMS) matrix

Note that with this representation , we implicitly considered that for all operations **j** such as **D(j,10)<>0**, then **D(j,3)=1**, which means that these operations can be done every week but their activation depends only on controlling biophysical variable state.

Once the CMS matrix is calculated by this algorithm, other simple instructions make it possible easily to calculate performances matrices for workload, net income, and pesticide use from the CMS matrix and variables P2, P6, P7, P8, and P9 of each operation selected in operation parameters matrix D.

4.2.7. Farming system integration model

The inputs of this model are the matrices obtained with the CMS model and the farm level parameters: farm acreage, decision rules of crop patterns, cost of manpower, levels of subsidies, banana sales prices, and efficiency of the conditioning facility. These parameters are also differentiated by farm types and are also modified by adoption scenarios (e.g. crop pattern rules are modified by adoption of rotations).

In the case of banana, farms can be represented by a set of groups of fields producing banana bunches that are harvested, selected, and packaged into boxes at a single conditioning facility. Several groups of fields have to be considered according to the date they were planted, because the age of banana plants determines its flowering. Thus any asynchronous flowering calls for different cropping; indeed, many operations are done on each individual banana flower (e.g. put a plastic bag around the flower to protect it from pests). For a five-year monoculture system, there are five kinds of groups of fields: the fields planted in the current year and thus not yet productive, the fields that are first flowering and thus very homogeneous, fields that are in their second flowering cycle and thus less homogeneous, and so on until five-year-fields that are asynchronous and will be replanted in the next year.

To model innovation adoption at farm scale, we considered a progressive adoption, which was represented according to a process of transition from one type of rotation to another during which both rotations coexist. This transition was formalized mathematically with transition matrices as proposed by Castellazzi *et al.* (2008). **Table 4** gives an example of the transition matrix for a farm type A currently practicing banana monoculture and adopting a system of banana in rotation with 24-month pineapple.

Years after adoption	Groups of fields of current cropping pattern: banana monoculture					Groups of fields of innovative cropping pattern: 2 years pineapple and 5 years banana							Total acreage
	BM1-year	BM2-year	BM3-year	BM4-year	BM5-year	P1-year	P2-year	BP1-year	BP2-year	BP3-year	BP4-year	BP5-year	
0	0.84	0.84	0.84	0.84	0.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.20
1	0.00	0.84	0.84	0.84	1.08	0.60	0.00	0.00	0.00	0.00	0.00	0.00	4.20
2	0.00	0.00	0.84	0.84	1.32	0.60	0.60	0.00	0.00	0.00	0.00	0.00	4.20
3	0.00	0.00	0.00	0.84	1.56	0.60	0.60	0.60	0.00	0.00	0.00	0.00	4.20
4	0.00	0.00	0.00	0.00	1.80	0.60	0.60	0.60	0.60	0.00	0.00	0.00	4.20
5	0.00	0.00	0.00	0.00	1.20	0.60	0.60	0.60	0.60	0.60	0.00	0.00	4.20
6	0.00	0.00	0.00	0.00	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.00	4.20
7	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.60	0.60	0.60	0.60	0.60	4.20

Note: Total farm acreage of farm type A = 4.2 ha. BM=Banana Monocrop, P=Pineapple, BP=banana after pineapple

Table 4. Transition matrix to represent evolution of land uses at farm scale in the case of a progressive transition from a five-year monoculture to a seven-year innovative system of rotation "24-months pineapple/five years banana" for farm type A.

Using parameters of the decision rules that define the different crop patterns on the farm, the integration model first simulates land allocation to the different cropping systems on the farm with the method presented above. Then it uses the transition matrices to combine the cropping system performances calculated with the cropping system model into a single farm by calculating farm level pesticide uses, workload, net income, and banana production, at a weekly step. The outputs can then by summarized at different time scales like month, year, or total duration of the banana crop pattern.

4.2.8. Software structure

As proposed by Van Ittersum et al. (2008), we opted for a framework to link individual models and data components through matrices in which outputs of a model are inputs of another one. Three softwares were used in this framework. The first one is a parameterization tool that serves to rapidly define all the parameters of the 11 decisional variables for all operations and farm level parameters. This tool, which we named "prototyping and parameterization module", has been developed in Visual Basic Editor ® and allows one to set up the parameters corresponding to the situation the user wants to model (choice of farm type and innovation that the user wants to test on the selected farm type). Some of these parameters are then used in the SIMBA model, developed in the STELLA® software version 7.0.2 from Isee systems (formerly High Performance System ®). We first simulated the biophysical performances of all possible crop management systems for all farm types and all innovations and stored their outputs in a “biophysical database”. The crop management system model and the farming system model were developed with the numerical computational package Scilab 4.1.2. (Campbell et al, 2006). A first algorithm calculates the performance matrices of all cropping systems involved in the scenario simulated. Then a second algorithm combines these matrices at farm level through the transition matrices presented in section 2.4. Although it is composite as it requires the sequential use of three different tools, this software infrastructure provides for flexible use and linkage of components.

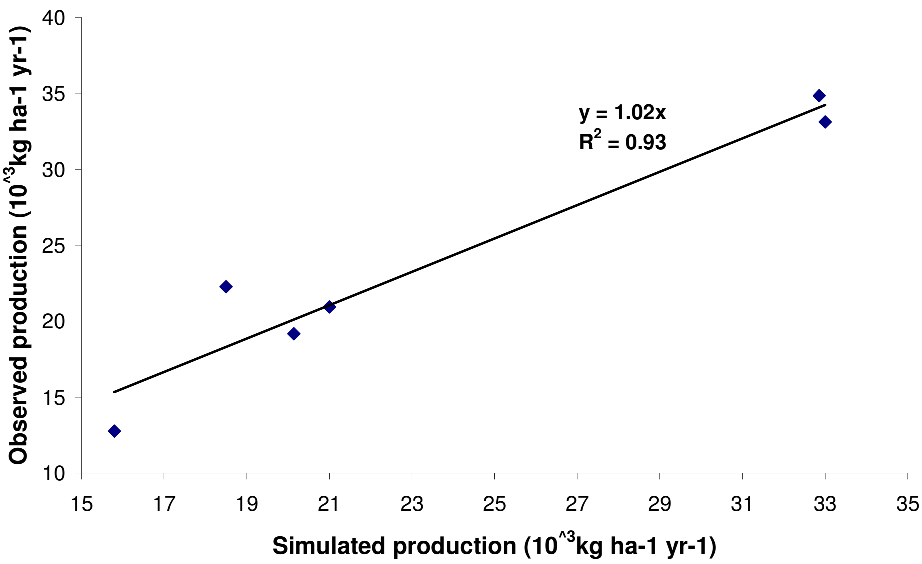


Figure 4. Comparison between simulated and observed production for 6 farms.

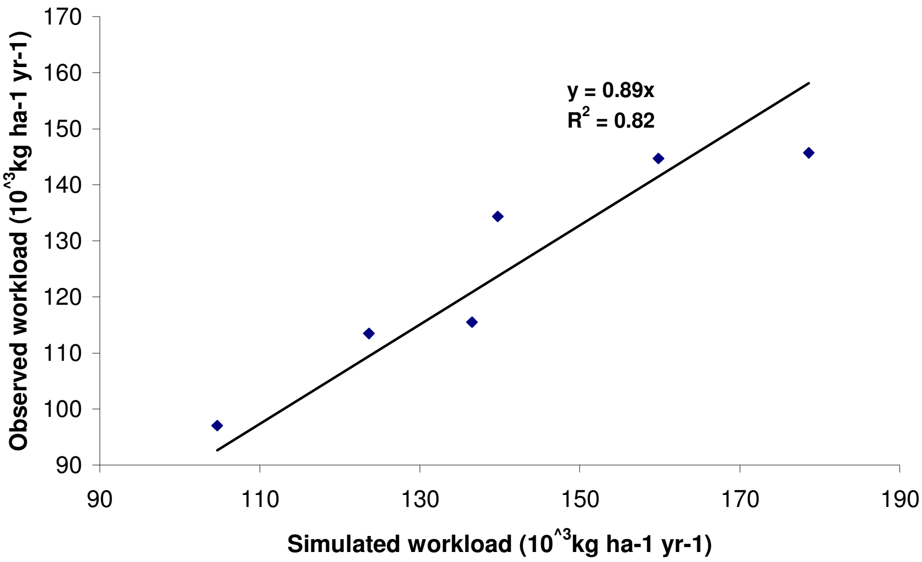


Figure 5. Comparison between simulated workload and observed workforce for 6 farms.

4.2.9. Model evaluation

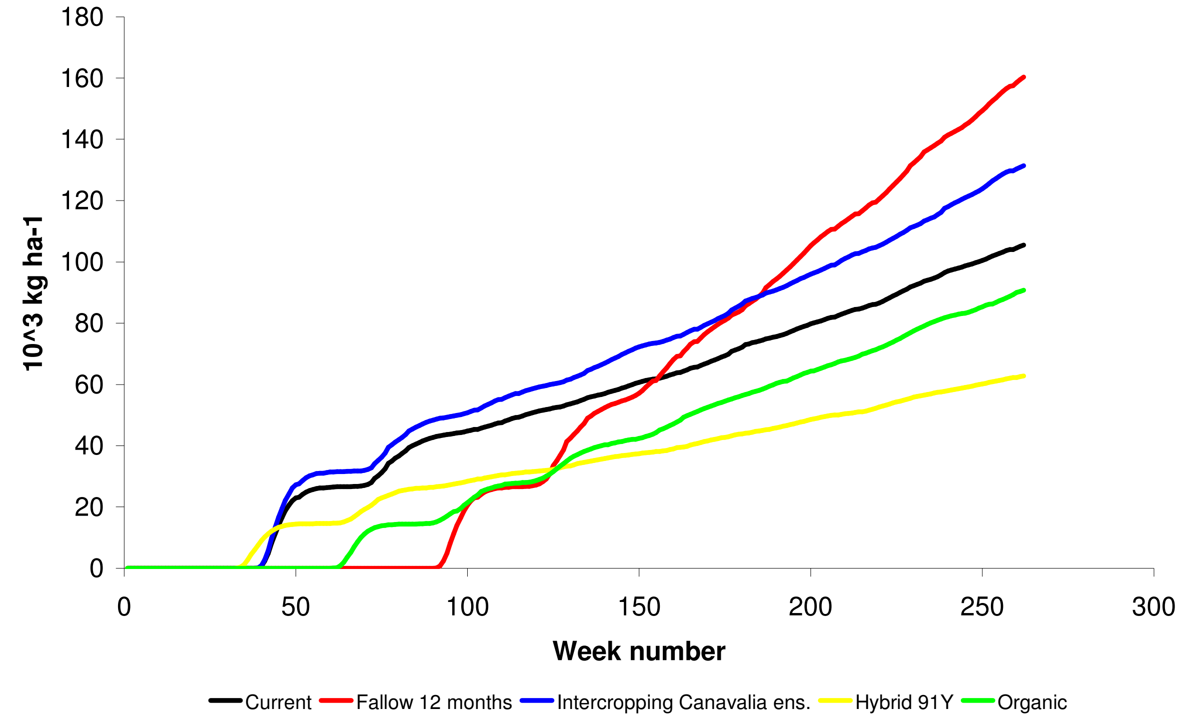
To analyze the robustness and the predictive performances of the model we compared the results of BANAD simulations to observed values for 6 farm types and three performance criteria, which were banana production, workload, and net income. These three criteria were retained because they reflect biophysical and technico-economic processes and their interactions. **Figure 4** shows a significant correlation between simulated and observed values for banana production at farm level (R^2=0.93, Pr>F = 0.002). The linear regression is close to one (1.02), which shows that the predictive performance of the model is correct for banana production. For workload (**figure 5)**, simulated workforce was significantly correlated with the one observed on the 6 farm types (R^2=0.82, Pr>F = 0.005). the linear regression is 0.89, which shows that the simulated workload values tend to be about 10% lower than available workforce. The simulation can therefore be considered correct since farmers have a bit more resources available than they need, for example to manage possible workload peaks or worker absences. **Table 5** shows the comparison between farm's net income obtained with quantitative simulations and a qualitative indicator provided by farmers through questionnaires. For farm type A, B, C, and E, the model correctly ranks the farms according to their income. However, the model predictions are not correct for farm types D and F, because it predicts an income of only 760€/ha for farm type D whereas farmer's income indicator is 'suitable income', and it predicts an income of 1235€/ha for farm F whereas, according to the farmer, there should be a deficit.

Farm code	Simulated (k€/ha/y)	Farmer's Indicator
A	2097	little income
B	4929	Suitable income
C	-971	Deficit
D	760	Suitable income
E	4850	Suitable income
F	1235	Deficit

Table 5. Comparison between simulated net income and income indicator provided by farmers.

This global evaluation shows that the predictive capacity and the robustness of the model are globally correct, because it correctly simulates and classifies several performance variables on a wide range of farm types. As some results relative to income were not satisfactory for farm types D and F, we made the *ex ante* assessment of innovations on farm types A, B, and C, which represent well the wide range of farming conditions in Guadeloupe.

a)



b)

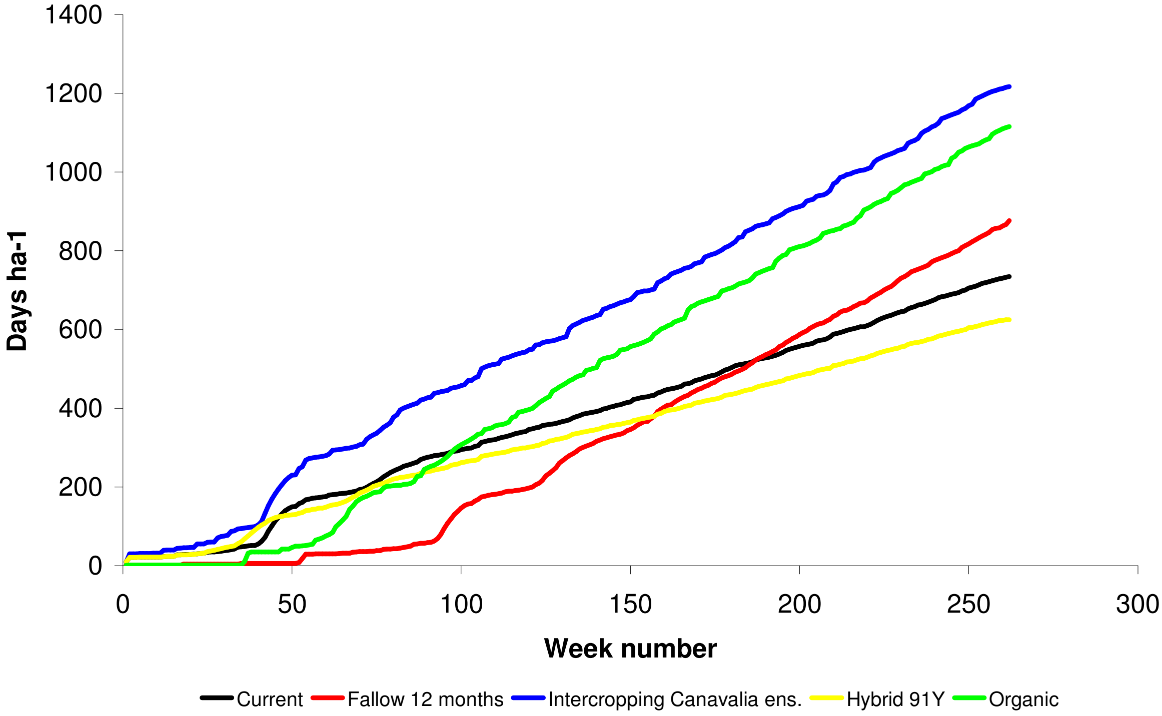


Figure 6. Cumulated cropping system performances simulated for farm type A.

a) banana's production, **b**) workload

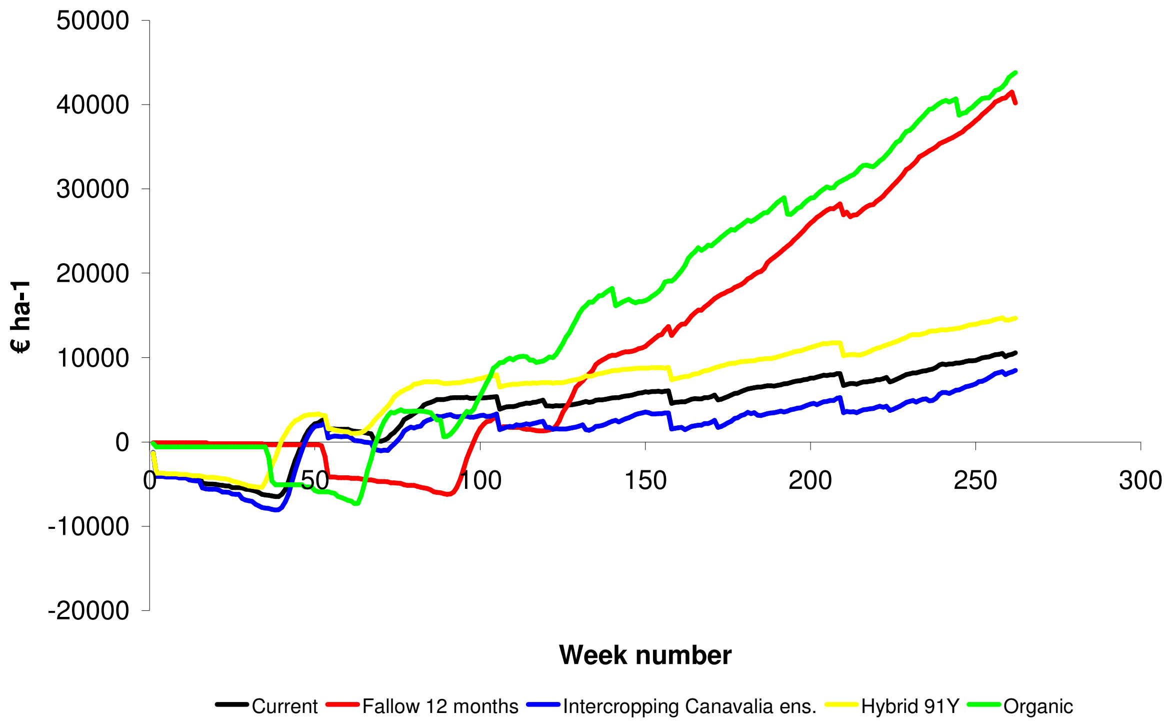
4.3. Results

4.3.1. Assessment of the performances of 4 innovative crop management systems in comparison to current system for farm type A at cropping system level

The "performances at the cropping system level" represents the performances assessed during the crop pattern's time scale of a group of fields planted on the same date that have the same CMS. **Figure 6a** presents the evolution of cumulated banana production for five cropping systems implemented on farm type A: current system, adoption of a chemically controlled 12-month fallow, adoption of banana intercropping with *Canavalia ensiformis*, adoption of hybrid cultivar 91Y, and adoption of organic banana (8-month fallow improved with *Crotalaria juncea*, banana intercropping with *Canavalia ensiformis*, hybrid cultivar 91Y, and organic fertilization). The impacts of these innovations on production differ with the time scale used in the analysis. On the long term, the best innovations are improved fallow and intercropping because they considerably increase banana production, whereas hybrid 91Y and organic system lead to a lower production. Although banana production is increased more by improved fallow than by intercropping on a long term scale, we observed the reverse on the short term because of the presence of banana's unproductive period in the system involving fallow. Improved fallow is less productive than the current systems during about three years (curve of improved fallow exceeds curve of current system at about week 160). Inversely, innovation hybrid 91Y gives a higher production on the short term but is less productive than the current system after week 45. This may be due to the specificities of yield components of hybrid 91Y: bunches are smaller but the cycle of flowering and maturation is shorter. However, final yield is clearly lower (about 40% less than current system). The large yield gains provided by improved fallow and intercropping can be explained on one hand by the sanitation effect of improved fallow on the nematode population in a situation that previously had no strategy to manage nematode pressure (monoculture and few nematicides), and on the other hand by the contribution of nitrogen biologically fixed by the intercrop in a situation where fertilization level is low and could limit yields.

The innovations presented in **Figure 6b** generate more workload, except hybrid 91Y. Indeed, increasing the banana production leads to an increased workload for harvesting and conditioning bananas, which represents between 30% and 50% of the total workload at farm level in the current situations.

c) net income



d) pesticide use

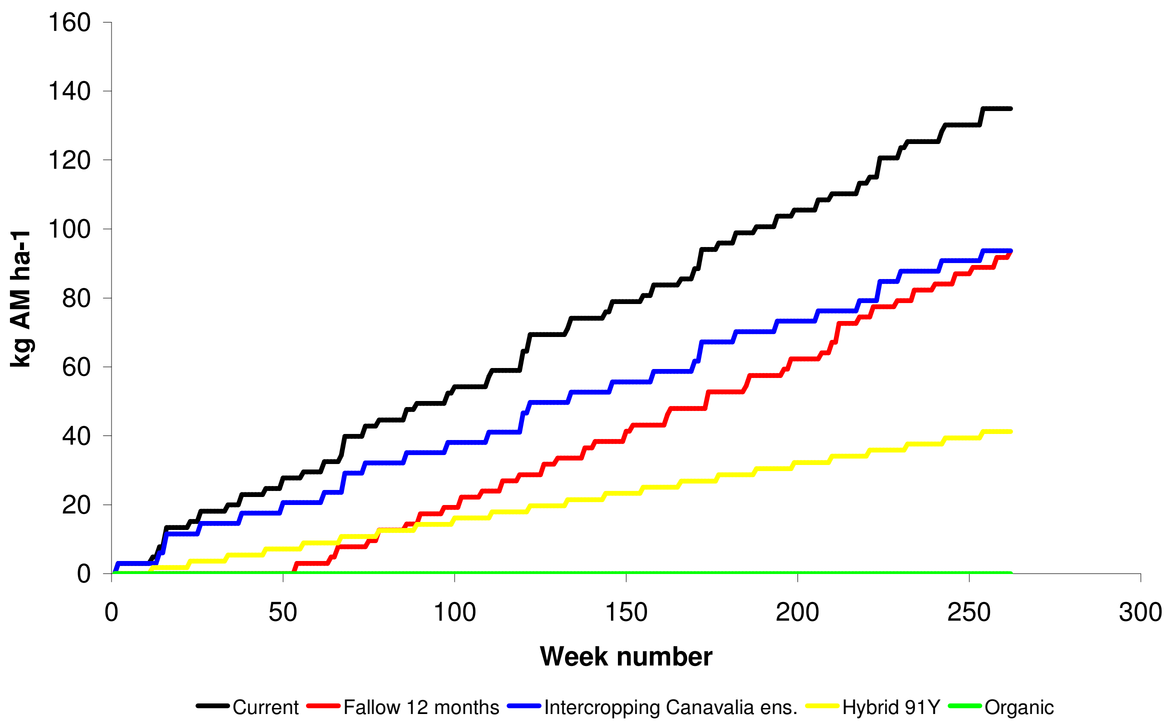


Figure 6. Cumulated cropping system performances simulated for farm type A.

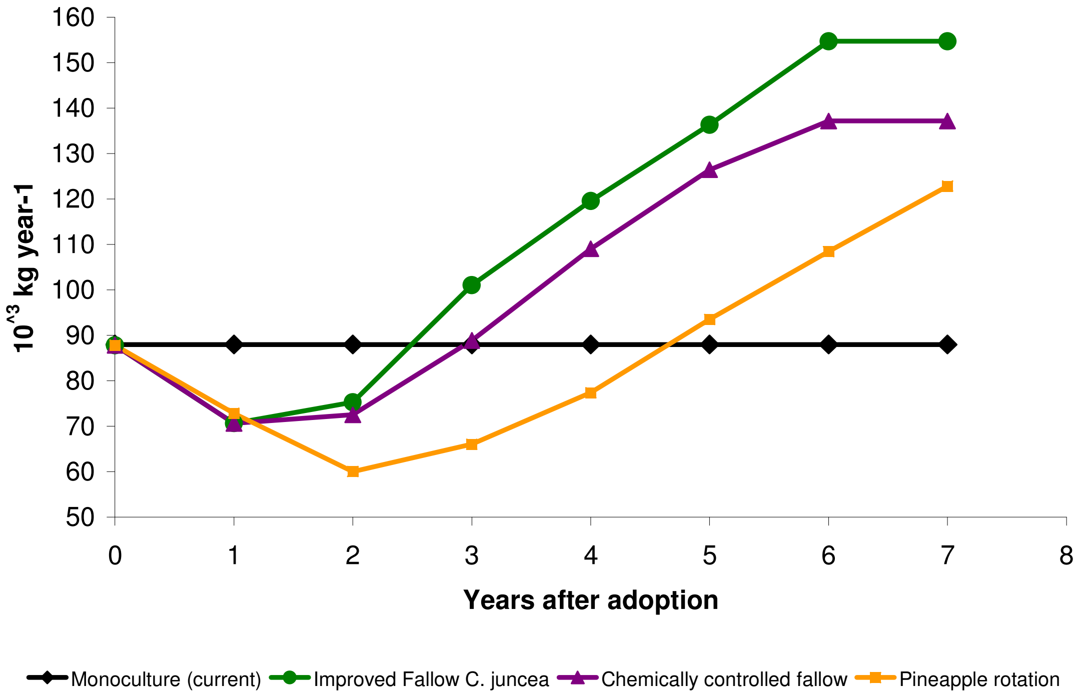
Innovations involving intercropping are particularly work demanding, because although they result in less production than improved fallow, they need more work for plantation and management of cover crops, while increasing the duration of other field's operations by making it more difficult for workers to circulate in the inter-rows. Surprisingly, although improved fallow reduces banana acreage by 20% relative to current systems, it generates a greater workload because of its higher productivity. At farm level, however, this situation corresponds to a switch between field work to harvesting and conditioning work and thus has a considerable impact on work management. The inverse is observed for hybrid 91Y because banana production is considerably lower than in the current system, but the workload at farm level is slightly lower, which corresponds to a decrease in work for harvesting and conditioning that is almost fully compensated by an increase in field work. Field operations are indeed more time consuming with this hybrid because of its considerable height, which makes operations on flowers and bunches longer.

As for the production of banana, the comparison of workloads between innovations and current system depends on the time scale of analysis, because impacts at short term differ from impacts at long term.

Figure 6c shows that an organic system and improved fallow lead to an increase in net income. An organic system leads to good economic results, explained by the doubling of banana sale price (from 0.558€/kg to 1.116€/kg), which largely compensates the banana production decrease and workload increase. Nevertheless the sensitivity of net income to sale price of organic banana needs to be further analyzed. It is interesting to note that although banana production is considerably reduced by hybrid 91Y net income is higher because of the higher sale price than with the current system (from 0.558€/kg to 0.837€/kg). For this smallholder farm type the considerable increase in banana production after adoption of improved fallow provides much better net income. The situation is different for intercropping, where the increase in banana production does not compensate for the workload increase, which makes the net income with this innovative system lower than that of the current system.

Figure 6d confirms that all innovations reduce pesticide use, by 100% for organic system, by 70% for hybrid 91Y, and by about 30% for intercropping and improved fallow systems.

a) banana production



b) workload

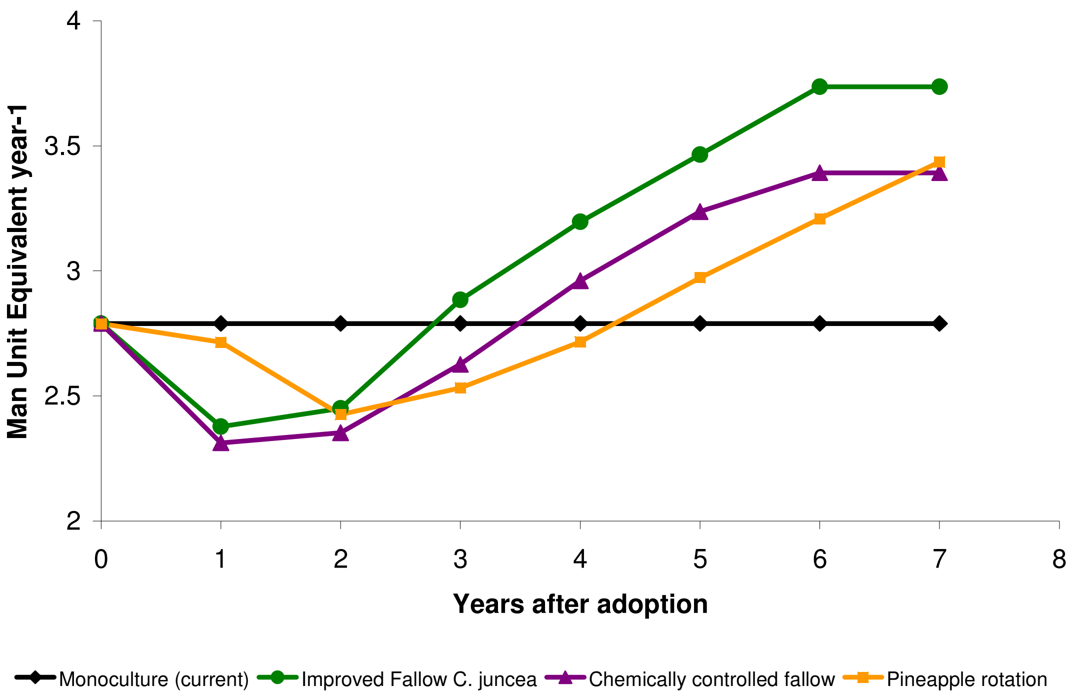


Figure 7. Simulations of the evolution of yearly farm performances after adoption for 3 kinds of rotations for farm type A.

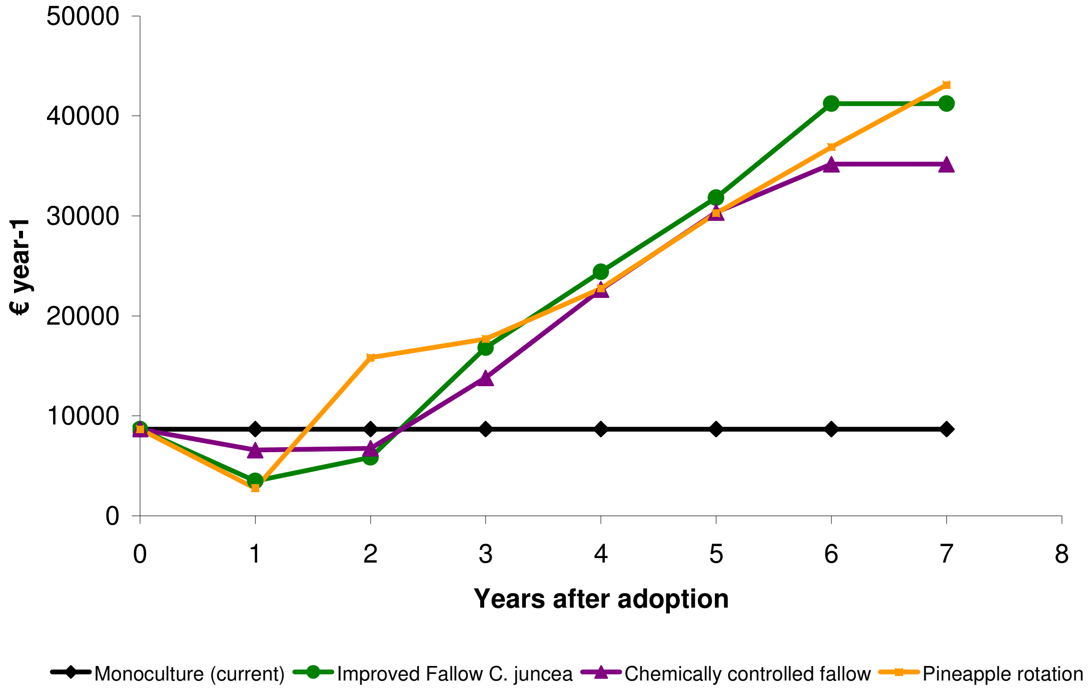
4.3.2. Assessment of the impacts, at farm level, of the adoption of the three types of banana rotation for farm type A

Figure 7a presents the evolution of banana production at farm scale for farm type A (acreage = 4.2 ha) after progressive adoption of three types of rotations, in comparison with the current situation (monocrop): 8 months of fallow improved with *Crotalaria juncea*, 12 months of chemically controlled fallow, and a 24-month rotation with pineapple. For all rotations, banana production decreases the first few years after adoption and then increases and exceeds considerably the current situation until establishment of a permanent situation. The duration of this lower production period depends on the innovations, i.e. 4.5 years for rotations with pineapple, 2.5 years for fallow improved with *C. juncea,* and 3.0 years for chemically controlled fallow. Then the production increases progressively each year and is stabilized 6 years after innovation adoption for the two fallows and after 7 years for rotation with pineapple. The final permanent production level is the highest for fallow improved with *C. juncea* because the fallow unproductive period is shorter (8 months against 12 or 24), and because it increases nitrogen soil content with the biological fixation of this leguminous cover crop during the fallow.

Workload at farm level (**figure 7b**) follows a trend similar to production, with a decrease the first few years after adoption and then a progressive increase until establishment of a final stable situation where workload is clearly higher than in the current situation. The final workload is higher for improved fallow because of the large increase in banana production, which increases workload for harvest and conditioning. As concerns the system with pineapple rotation, although banana production in this system is lower than for the system with chemically controlled fallow, the final workload is the same. This can be explained by the fact that pineapple is work consuming, for plowing, plantation, weed control, fertilizer supply, and harvest operations. Note that the workload one year after adoption is the same for rotation with pineapple than in current system but is then lower up to four years after adoption.

Figure 7c shows that although rotations make it possible to increase net income (from about 9000€ year^{-1} to about 40000€ year^{-1}), they induce a transition period of 1.5 to 2.5 years during which net income decreases drastically the first year after adoption to 3477€ year^{-1} for improved fallow, 6567€ year^{-1} for chemically controlled fallow, and 2745€ year^{-1} for rotation with pineapple.

c) net income



d) pesticide use

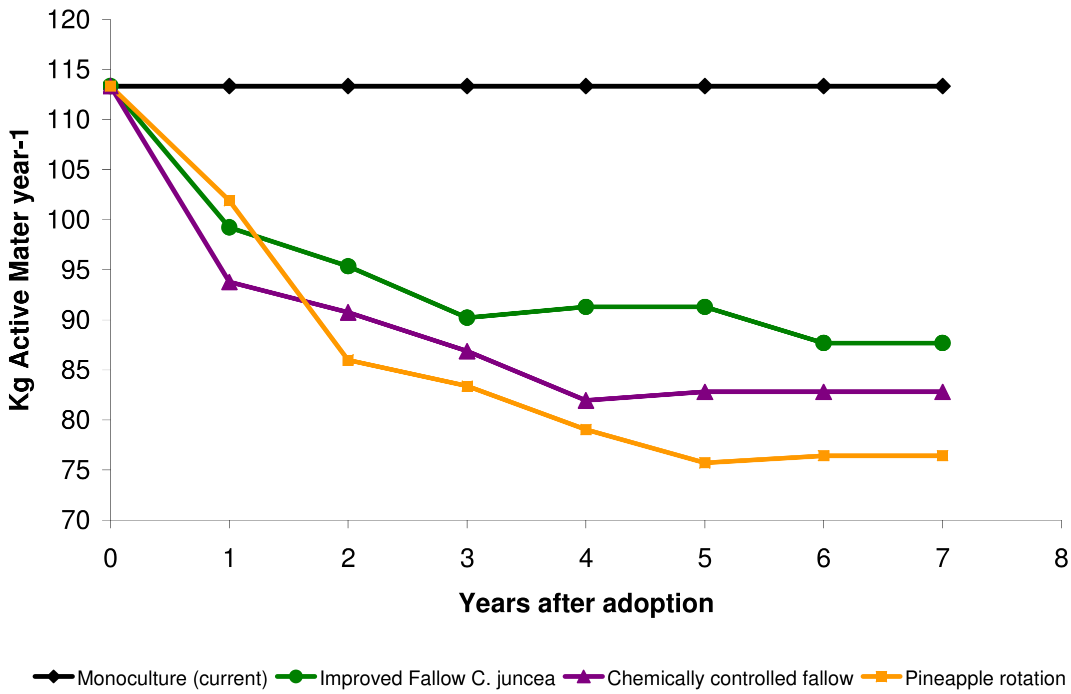


Figure 7. Simulations of the evolution of yearly farm performances after adoption for 3 kinds of rotations for farm type A.

These differences are explained by the loss of 20% of productive banana acreage and the additional costs of plantation for both fallow with *C. juncea* and rotation with pineapple. However, rotation with pineapple increases income level (15828€ $year^{-1}$) the second year after adoption, due to pineapple sales, whereas income is still below that with the current system (8669€) for improved fallow and chemically controlled fallow (5828€ and 6745€, respectively).

The adoption of these innovations makes it possible to progressively reduce pesticide uses at farm level (**Figure 7d**), from 113 kg $year^{-1}$ to 88 kg $year^{-1}$ for fallow improved with C. juncea, 83 kg $year^{-1}$ for chemically controlled fallow, and 76 kg $year^{-1}$ for rotation with pineapple. The latter, however, is above the other rotations the first year after adoption because of the considerable use of herbicides in pineapple management systems.

4.3.3. Assessment of two innovations across three farm types

Table 6 presents the results of the assessment of the innovation "intercropping with legume cover crop *Canavalia ensiformis*" on farm type A, B, and C. The innovation's impacts differ greatly among farm types. This innovation is not profitable for farm type A and B (income reduced by 412€ and 831€ ha^{-1} $year^{-1}$, respectively) whereas it increases farm type C by 3472€ ha^{-1} $year^{-1}$, in comparison with the current situation. This can be explained by the banana yield increase induced by this innovation for farm type C (16 tons ha^{-1} $year^{-1}$), resulting from improved nitrogen nutrition of banana plants in a situation where nitrogen stress was high in the current system. This situation is due one the one hand to the low level of fertilization of farm type C because of a lack of cash flow and on the other hand to abundant rainfall, which induces nitrogen losses due to leaching (Dorel et al., 2008). This innovation seems therefore to be appropriate for this farm type, provided it can afford the increased workload induced by its adoption.

Farm Type	Banana production (10^{3} kg ha^{-1} yr^{-1})	Workload (d ha^{-1} yr^{-1})	Net income (€ $ha^{-1}y^{-1}$)	Pesticides (kg $ha^{-1}yr^{-1}$)
Type A	+5	+96	-412	-8
Type B	+4	+42	-831	-7
Type C	+16	+75	+3472	0

Table 6. Integrated impacts of adopting banana intercropping with legume cover crop *Canavalia ensiformis* for three farm types.

The profitability threshold (in comparison to current situation) of banana sale price for the organic system was 0.737€, 1.135€, and 0.777 €.kg^{-1}, for farm type A, B, and C, respectively. These differences can be explained by the interaction of three factors:

- the lower profitability of current CMSs for farm type A and C than for farm type B (respectively 2097 € ha^{-1} year^{-1} and -971 € ha^{-1} year^{-1} in comparison to 4929 € ha^{-1} year^{-1}), which makes the profitability threshold more difficult to reach when innovation is associated with reduced productivity, as in organic systems,
- differences in manpower costs, which are low for farm type A and C and high for farm type B, which can account for the higher profitability threshold of farm type B. Indeed, the large impact of work increase will impact more on production costs and thus decrease the net income,
- and yield level associated with this innovation, which reflects to which extent systems will benefit from the increase in banana sale price (farm type C has the lowest yield so it will benefit less from the increase in sale price).

4.4. Discussion

4.4.1. Agronomic and policy recommendations for banana production in Guadeloupe

These results indicate several agronomic and policy recommendations for improving the likelihood of adoption of the innovations in banana farming systems of Guadeloupe. First, we identified which innovations would be relevant for farm type A, which represents smallholders that constitute about 50% of the total population of growers.

Our study provides contrasted results. Adoption of fallow seems to be relevant for farm type A because it induced an increase in production and income after respectively 3 and 2.5 years. However, it induced a strong decrease in net farm income during the first 2.5 years. This transition period can be a key constraint to adoption for smallholders, as observed in other studies (Lojka et al., 2008). Adoption of a cash crop rotation (pineapple) could reduce this transition period from 2.5 to 1.5 years, but it would induce a stronger decrease in net income in the first year. One solution would be to provide smallholders access to credit to maintain their vital income during this critical period or to give them a subsidy for conversion during the three years following adoption.

Then our study showed that it is important to identify in which farm type each innovation will be adapted, and under which conditions. For example innovations based on intercropping with legumes are more suitable for farm type C, whereas for farm types A and B, adopting this innovation would lead to a substantial loss of income. This loss of income is due to workload increase, which is generally the case for conversion to low input systems as they are assumed to substitute chemical inputs by other factors such as management knowledge, labor, or land (Padel and Lampkin, 1994). Incentives to promote the adoption of this innovation for banana growers in Guadeloupe should include financial compensation from 400€ ha-1 year-1 to 800€ ha-1 year-1 for farm type A and B, respectively. The alternative would be to re-design this innovation to reduce its workload by using less “cumbersome” cover crops. For example herbaceous cover crops like Bracharia decumbens may be better, as they could be regularly mechanically pruned, while maintaining their important role of covering the soil and thus limiting weed development and erosion risk., Mechanical pruning, however, is not possible on every farm type, due to slopes or financial constraints as in farm type C.

New hybrid cultivars are interesting from an environmental point of view as they strongly decrease pesticide use, but they are not productive enough to make the CMS profitable. Even though combining this innovation with intercropping, improved fallow, and organic fertilization would increase the CMS’s productivity and avoid pesticide use, it should nevertheless be accompanied by a substantial increase in the sale price from about 0.56€/kg to at least 0.78€/kg for farm type A and C and 1.14€/kg for farm type B, in order to maintain the current level of farm income. Consumer willingness to pay for such products should be investigated in another study, which could be done with econometric hedonic models (Rosen, 1974; Langyintuo et al., 2005).

4.4.2. Model effectiveness and limits

In this section we discuss the validity of BANAD, underline the principal results, and finally discuss the genericity of the model. Evaluating such a model’s validity is not easy because it integrates many biophysical, technical, and economic processes into output variables used as assessment indicators. Furthermore we tested several crop management systems on three farm types, and BANAD has not been validated for all innovations on all farm types. Fallow innovation was validated on farm type B because this farm type currently involves improved fallow, and this has been correctly simulated. New hybrids have been validated in Tixier et al. (2008b). However, intercropping and integrated systems have been mainly calibrated with on station experimental data and not validated on farm.

Nevertheless, we evaluated our model by comparing the results of the model developed with data observed on 6 commercial farm types, for the three of the four criteria used in this study. This evaluation shows that BANAD was generally able to correctly rank the systems for the three criteria.

Furthermore, the aim of this *ex ante* study was precisely to determine virtually the behavior of these innovations on real farm conditions. To this end, our modeling approach has two advantages. First by integrating a component in the model to describe real contrasted situations (the farm typology) we could confront innovations with real farm conditions. Then the structure of this model makes it possible to confront innovations to a systemic mechanistic framework and therefore to take into account possible interactions between innovations and bio-economic processes, which would be almost impossible to do with on-farm trials. Such trials are now required to validate our results. The advantage of our approach is that it allows one to identify the most promising "innovations * farm types" situations to be assessed and to conjointly rethink the design of innovations that are still problematic in terms of agronomic adaptations, before testing it on farm.

The implementation of our modeling approach on banana farms has shown the importance of factors often neglected in *ex ante* assessment studies, like the dynamic nature of innovation adoption and impacts, the importance of workload quantification of innovations, and the variability of the impacts among farm types for a given innovation and among innovations for a given farm type. These factors need to be simulated at the early stage of a prototyping research program in order to increase the relevance and the likelihood of adoption of technological innovations. Assessing at farm scale and in a dynamic way the impacts of adopting several contrasted innovations on farm functioning and farmers' main resources, as if they would be adopted by them, will make assessment studies more operational. One could rapidly identify, on a wide range of real conditions, the critical factors or periods associated with the innovation, and the economic, biophysical, and technical conditions under which each innovation is "adoptable" by the virtual farmer simulated with BANAD. Such a modeling approach can open new area of research in which the innovation and the policies can be co-assessed and co-designed on the basis of multicriteria assessment. The model can be used as a stand-alone version or integrated into a more complex framework across spatial scales (e.g. the Seamless platform, van Ittersum et al., 2008). When it was possible to validate the model for an innovation, our approach allowed policy recommendations to be calibrated so as to improve their likelihood of adoption. However, adoption and diffusion are complex processes in which farmers' perception of the utility of an innovation, given its quantitative attributes, also depends on many factors relative to farm endowment and farmer attitudes toward risk and uncertainty (Feder and Umali, 1993; Marra et al., 2003; Edwards-Jones, 2006). To characterize these personal preferences, the results of this study are currently used in a survey of the potential of innovation adoption by farmers with random utility econometric model (Adesina and Baidu-Forson, 1995 ; Herath and Takeya, 2003; Lapar and Ehui, 2004). Another limit of our study is that we have not focused on planning constraints and on the impact of climate interannual variability. This has to be done in the future and some authors have provided interesting approaches (Joannon, 2005; Aubry et al., 1998).

Building a mechanistic and dynamic bio-economic farm model and contextualizing it by farm type to better account for the different farming situations at regional level is not an easy task. This has, however, been partially possible in the case of innovations on banana farms in Guadeloupe. First, we had a robust, powerful and dynamic crop model, previously parameterized for the local CMS (Tixier et al., 2008a), that takes into account the key biophysical processes, like fruit production and pests and weeds dynamics. Furthermore it can take into account interactions between biophysical processes, crop management systems, and farm physical and parasitic contexts. Second, after about 20 years of research on innovative techniques we had a considerable capital of biophysical and technical knowledge on these innovations. Third, we had a farm typology that models current farm regional diversity in terms of crop management systems, performances, and economic and biophysical contexts. Finally we have to underline that banana farms are very specialized in banana production and therefore interactions with other cropping or livestock systems did not have to be modeled, which has considerably simplified the building of the farm model.

Although BANAD could seem very specific to banana farm, the simple component structure of the model with a farm typology, a crop model, a crop management system model, and a farm level integration model is simple and generic. Other elements that make BANAD simple and generic are the formalisms of automatic generation of consistent CMS parameters, differentiated by farm types and innovations through operations parameters and simple decision rules to parameterize the crop management system and the farm biophysical and economic conditions. Thus the mathematic formalisms to model cropping and farming system through decisional variables and different kind of matrices could be used in other contexts. Applying such modeling in other contexts would be easy and rapid if one disposes of expert knowledge and data on crops and on farms, a frequent situation when current systems are well established but not durable anymore.f

4.5. Conclusions

We developed a simple mechanistic dynamic farm model to assess ex ante the impacts of innovation adoption on different farm types. Results obtained from the application of the method to banana growers in Guadeloupe showed that it is important, in ex ante assessment of innovations, to take into account the dynamic and the multi-criteria dimensions of the impacts of adoption. Assessment of several innovations among a farm type showed that, according to the time scale of analysis, the results can differ. Adoption of rotations can be problematic during a transition period following adoption, which considerably reduces farm level income for smallholders. Our study also confirmed the need to assess innovations under different scenarios and on different criteria. Adoption of new hybrids and organic systems drastically reduces pesticide use, as well as productivity, but it can be profitable under different marketing scenarios. Intercropping with legume cover crop is interesting for its capability to reduce herbicide use while increasing cropping system productivity, but its profitability is lowered by the increased workload. However, intercropping with legumes can be efficient on all criteria for a farm type. This shows the need to assess innovations under different real farming situations, which BANAD makes possible in short time and with few resources in comparison to on farm trials, provided it is applied in a regional situation where farms and crops are well characterized. This kind of approach can be useful to facilitate the formulation of strategic orientations for agronomic innovation research and policy definitions, but it requires a certain amount of knowledge on current and innovative systems and the availability of a previously calibrated modular crop model. Nevertheless we believe that the methodology and the formalisms proposed to build BANAD are relatively generic and should be useful to other modelers and prototyping scientists.

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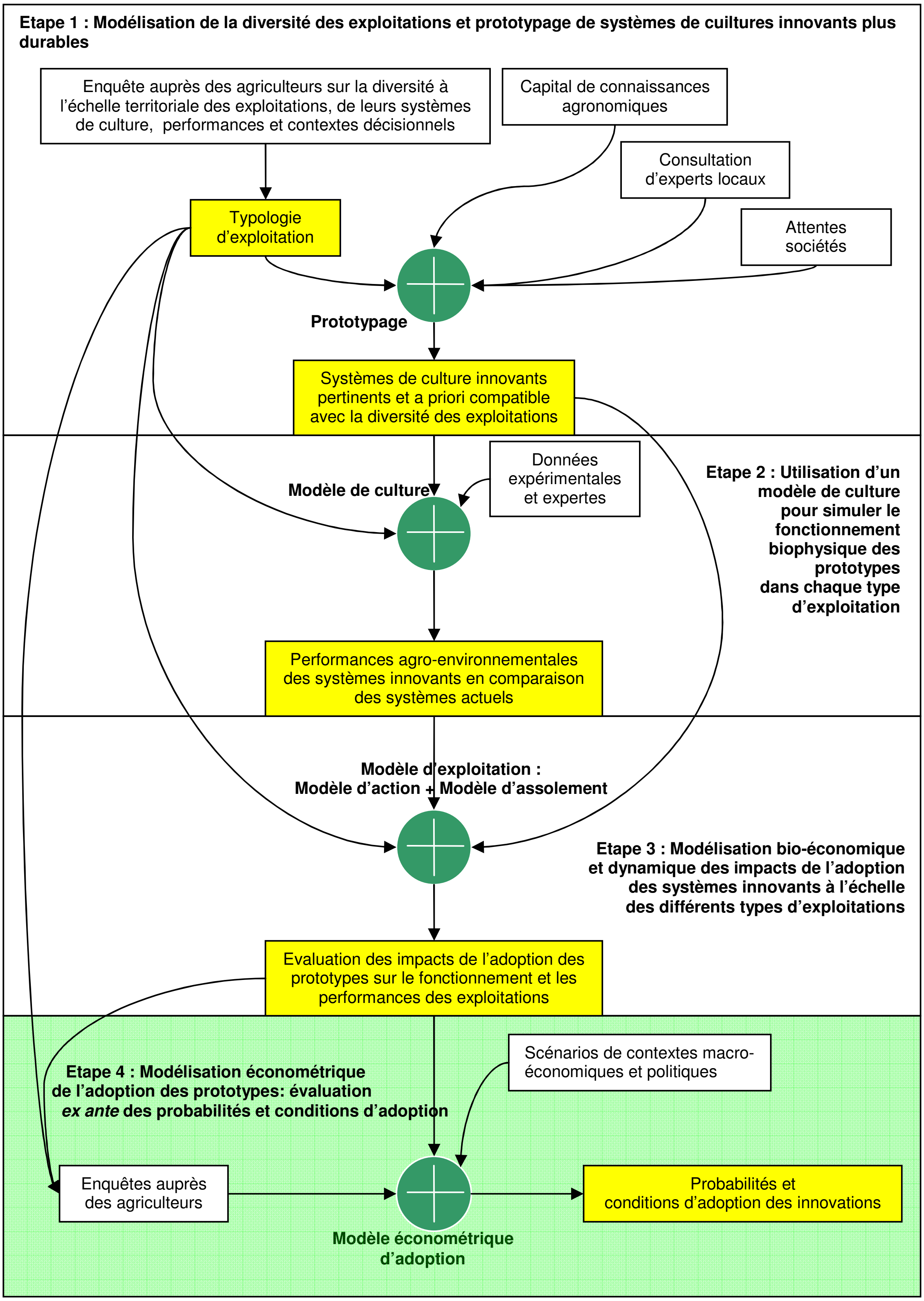

Figure D : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

5. Modélisation économétrique de l'adoption des prototypes: évaluation ex ante des probabilités et conditions d'adoption

Ce chapitre constitue la quatrième et dernière étape de la démarche. Il vise à élaborer un modèle économétrique d'adoption qui nous permettra de définir des conditions d'adoption des prototypes de systèmes de culture innovants.

Après une revue de la littérature sur l'adoption de l'innovation en agriculture, nous définissons un ensemble de facteurs d'adoption potentiels. Nous construisons ensuite un questionnaire d'enquête visant à identifier le potentiel d'adoption de 5 innovations présentées aux agriculteurs sous la forme de contrats agro-environnementaux impliquant adoption des systèmes de culture innovants avec réduction de l'usage de pesticides et compensations financières. La partie du questionnaire visant à décrire aux agriculteurs les performances des systèmes innovants a été construite en utilisant les résultats des simulations bioéconomiques réalisées dans l'étape 3. Nous testons 5 innovations qui correspondent aux 5 types d'innovations évaluées dans la méthode : jachère avec plante de couverture, nouvelle variété hybride, cultures associées, système intégré impliquant jachère et cultures associées, et un système de banane BIO[8].

Cette quatrième étape de la démarche globale est présentée dans l'article suivant, intitulé **« An ex ante adoption model of low input innovations applied to banana growers in the French West Indies »**, qui a été soumis à la revue ***European Journal of Agricultural Economics*** (http://erae.oxfordjournals.org/).

[8] Nota : le système BIO testé ici diffère de celui présenté et évalué dans les chapitres 2, 3 et 4 (prototype F3) par deux différences : il n'inclue pas l'adoption de la nouvelle variété hybride, et le prix de vente associé à ce système est de 120% le prix de la banane conventionnelle au lieu de 150% pour le prototype F3. Les performances agronomiques et économiques associées à ce système BIO sans nouvelle variété sont alors considérablement augmentées. Cette innovation n'a pas été présentée dans les autres chapitres car nous avions très peu d'éléments de validation des modèles pour cette innovation. Cependant, nous avons fait le choix de l'utiliser dans cette étape car elle nous permettait de tester une large de gamme de performances.

An ex ante adoption model of low input innovations applied to banana growers in the French West Indies

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Abstract
This paper proposes an *ex ante* adoption model of five different innovative crop management systems aimed at reducing pesticide use for banana production in the French West Indies. A conditional Logit model estimated on an original sample of 607 farmers allowed us to characterize the determinants affecting the likelihood of adoption. Our results show that adoption of innovation is determined by policy attributes, farmers' expectations, attitudes toward innovation, and the interactions among these factors. The paper finally discusses the limits of our *ex ante* approach and proposes several policy and agronomic recommendations to promote environmental adoptions.
Keywords: innovation, adoption, model, ex ante, pesticide.

5.1. Introduction

French West Indies (FWI) production of bananas for export has been affected since the 1990s by the liberalization of banana markets, as the competitiveness of these two small Caribbean islands Guadeloupe and Martinique – is generally low compared to production from Central America. This lack of competitiveness can be explained by higher labour costs, land scarcity, development of parasitic pressure, and frequent hurricanes. As a consequence, farmers have relied for their agricultural practices on monocropping, ploughing and massive use of expensive and nocive chemical pesticides to fight against pests development (Houdart *et al.*, 2008). Decades of such practices have led to yield loss (Clermont Dauphin *et al.*, 2004), chronic lack of cash flow (Dulcire and Cattan, 2002; Cattan and Dulcire, 2003), water and soil contamination (Bonan and Prime., 2001; Bocquene *et al.*, 2005) and income erosion (Bonin and Cattan, 2006). Combined with an increasing social pressure for more environmentally-friendly practices and the prohibition of numerous biocides, this situation has led farmers to an economic, social and technical crisis. As a result, the number of banana farmers has decreased drastically, from about 1400 farms (8000 ha) in 1981 to about 220 farms (3000 ha) in 2006 in Guadeloupe only. This drastic decrease is threatening the local economy, as banana exports are an important source of income and employment for these islands, where the unemployment rate is over 25% and the trade balance is badly in deficit (INSEE, 2007). The ability to move to alternative farming systems is limited however, as the persistent contamination of soils by chemicals reduces the scope for diversification (DAF, 2003; 2005). Furthermore, insularity and the weak structuration of supply chain of other production sectors make access to new markets difficult. Current banana's management systems therefore need to be adapted to this situation, and agronomic research is currently focusing on alternative management systems aimed at improving the sustainability of production, by reducing chemical input use, restoring soil fertility to improve yields, and developing new varieties to differentiate FWI production on international markets. Five systems currently under development involve one or several innovative technologies: a) intercropping banana with legume crops to limit herbicide and chemical fertilizer use; b) new banana hybrids tolerant to Sigatoka disease to limit fungicide use and with new commercial characteristics; c) improved fallow to control the pressure of the endoparasitic nematode *Radopholus similis* and to limit nematicide use, and d) replacement of chemical fertilization by organic inputs.

As a contribution to this innovation process, we tried to determine *ex ante* the likelihood of adoption of these five innovative systems by examining the socio-economic determinants behind their adoption. It is now well known that farmers often fail to follow the technical advice put out by the extension services, and do not always adopt technical innovations (Renaud *et al.* 1998; Orr and Ritchie 2004; Bonin and Cattan, 2006). This makes assessing *ex ante* the factors that can enhance innovation adoption an useful step to (re)direct appropriate technology development and define suitable policy strategies to improve the likelihood of adoption of innovations entailing lower chemical input use.

Discrete choice modelling is an appropriate tool for analysing the decision to adopt innovation. It has been extensively developed and constitutes an important body of the empirical literature in agricultural economics. Since the first works of Griliches (1957, 1958), three main paradigms have been proposed for modelling adoption decisions. The first one is the innovation-diffusion model proposed by Rogers (1962), according to which adoption of an innovation is explained by access to information, and could be modelled as a function of time. Feder and O'mara (1982) and Feder and Slade (1984) provided theoretical basis for Griliches and Rogers time-dependent models and extended it to an economic constraint model (Feder *et al.*, 1985), in which adoption decisions can also be explained by the asymmetrical distribution patterns of resource endowments such as farm size, access to credit, risk aversion and the variability of farmers' personal attitudes. This paradigm has been applied in discrete choice models on the basis of the work of McFadden who used Thurstone's random utility formulation (1927) to model decisions through the maximization of an utility function. The third paradigm is the 'adopter perception' paradigm (Lynne *et al.*, 1988; Adesinah and Zinnah, 1993), which states that farmers' perceptions on innovations' attributes can strongly affect adoption decisions. A review of the literature on innovation adoption studies (see in particular Feder and Umali, 1993; Abadi Ghadim and Pannell, 1999; and Marra *et al.*, 2003) reveals that this complex process depends on a large set of factors relative to farmer perception, farm structure and its socio-economic environment, the characteristics of innovation, and policy characteristics. However, most published empirical studies on adoption pay attention to only a few of these determinants at the same time and seldom consider interactions among them. Moreover, these studies are generally ex post and seldom consider joint adoption of several innovations, which is different in an *ex ante* situation where several very different candidate innovations can be under development. In the few *ex ante* studies using the 'adopter perception' paradigm, farmer's perceptions toward innovation performance are generally described in qualitative terms only (Adesina and Baidu Forson, 1995). This could be explained by the fact that it is difficult to assess *ex ante* the variability of innovation performance under real economic and biophysical conditions. Breusted et al. (2008) used quantitative attributes but for studying a single innovation. Finally, we have to point the fact that farmer's expectations and objectives are rarely taken into account in the modelling of adoption. Therefore, a gap exists in the methodology of ex ante adoption studies, with the lack of a generic and robust model of innovation adoption that accounts for a large set of determinants and (possibly competing) innovations together with their potential interactions.

The contribution of this paper is an attempt to provide an answer to this gap in the literature. It presents an empirical *ex ante* adoption model applied to 607 banana growers in the FWI, depicting farmers' adoption behaviors by a set of five discrete adoption decisions corresponding to five different innovations. An original feature of the application is the fact that the ex ante adoption analysis has been conducted by identifying stated preferences of a large proportion of banana farmers for innovations that have been developed by agronomy scientists.

We accounted for a large set of determinants relative to farmers' attitudes, expectations and socio-demographic characteristics, farm assets and constraints, informational and geographical contexts, and quantitative attributes relative to innovations and policy generic characteristics, that have been assessed and calibrated with a preliminary bio-economic modelling study (Blazy, 2008a). Specific attention was given to farmers' expectations and objectives that are seldom taken into account in adoption studies, and whose effect on adoption is important to evaluate.

The rest of the paper is as follows. Section 2 presents a survey of adoption studies used to model innovation adoption. In section 3, we describe banana's innovative systems and adoption factors in the FWI. The design of the survey on a sample of banana growers in FWI and the adoption model are also introduced. The model of adoption is presented in Section 4, and forms the basis of our econometric strategy. Section 5 presents the estimation results of the discrete-choice model, including the discussion of the marginal effects and elasticity calculations. We discuss in section 6 the limits and the genericity of our *ex ante* adoption modelling approach and propose several agronomic and policy recommendations. Section 7 concludes.

5.2. A survey of adoption studies

A review of empirical and theoretical studies on innovation adoption in agriculture reveals that the individual decision-making process that leads a farmer to adopt an innovation entails five categories of determinants:

i) Farmer's socio-demographic characteristics and personal attitudes,
ii) Farm structure and technological constraints,
iii) Geographical, institutional and social environment,
iv) Attributes of innovation
v) Policy and market attributes.

Innovation adoption can be seen as the result of interactions beetween various factors located at different scales and involving different stakeholders, see for example Joly and Lemarié (2000). Specific farmer's socio-demographic characteristics have been identified as major determinants in many studies. The age of the farmer generally influences negatively adoption decisions (Ayuk, 1997; Thangata and Alavalapati, 2003); the sex of the farmer influences adoption differently depending on the innovation and the context studied (Adesina and Mbila 2002, Adesina and Chianu 2000). The farmer's education level (Feder et al. 1985, Feder and Slade 1984, Lapar and Ehui, 2004) has in general a positive influence on innovation adoption.

There are numerous determinants related to farmer's personal attitudes. Attitude toward risk, change and uncertainty can significantly influence adoption as they can reduce the perceived utility of innovations, and be associated with aversion to change (Feder, Just and Zilbermann, 1985; Sunding and Zilbermann, 2001; Abadi Ghadim et al., 2005). Other authors have proposed to decompose the population of farmers into several subgroups according to their general attitude toward innovation: early adopters, followers and late beginners. Such decomposition allows to capture attitudes related to the search of a better social status on being seen to be innovative (Diederen et al. 2003b, Abadi Ghadim and Pannell, 1999). Moreover, farmer's expectations about future policy and market change can play an important role, as they can modify farmer's perceived utility of innovations. For example, market conditions and policy context are constantly in evolution in the FWI since the 1990s, with the prohibition of several pesticides, a decrease in public subsidies, and a more volatile banana market price due to a decrease in trade barriers. This has led banana farmers in the FWI to have a poor visibility of the economic perspectives of the sector. Finally, farmers' personal ambitions about the future of their farms can influence significantly their perceived utility of innovations (Amador et al., 1998).

The second type of determinants of adoption is related to production inputs and constraints such as financial capacities, access to credit and cash flow limitations (Feder and Umali, 1993; Boahene *et al.*, 1999), access to water (Auyk, 1997), farm size (Adesina and Chianu, 2000; Feder and Umali, 1993), physical constraints (Adesina and Mbila, 2002), off-farm labour (Herath and Takeya, 2003), and the size and nature of labour force (Feder, Just and Zilbermann, 1985; Thangata and Alavalapati, 2003).

A third category of adoption determinants concerns the farm's local environment, and have been studied in the literature as part of the geographical, institutional, social or economic contexts. These contexts are mainly captured through geographical indicators such as regional appartenance, distance to other innovators, distance to market, demographic pressure, the presence of extension services (Adesina and Mbila, 2002; and Lapar and Ehui, 2004). They are also related to farmers' characteristics such as the number of contacts with extension agents, the involvement of farmers in research programs, or the affiliation to a farmer's union.

Innovation attributes are often considered the most important of all adoption factors, because they are at the heart of expected changes in agricultural practices, including the way farm assets and constraints are considered by the farmer. In general, innovation attributes may impact expected income, productivity, workload, input use and production costs. They can also be relative to the nature of innovation, as shown by Morse and Mc Namara (2003), Sidibé (2005), Adesina and Baidu Forson (1995), and Edmeades et al. (2008). The challenge for agricultural economists is precisely to translate innovation attributes (often expressed in technical relationships) into economic variables. When agricultural or cropping practices are modified by an innovation, trade-offs between, e.g., more labour-intensive traditional technologies and more capital-intensive technologies, need in most cases to be expressed in terms of relative input uses (and associated costs). As regards constraints that can be either alleviated or strengthened by an innovation, their associated shadow prices can also be part of the innovation attributes. Finally, in the likely case where several policy options or schemes are considered, a part of innovation attributes should be made relative to incentives and market characteristics. This clearly includes the duration of the contract and the level of financial compensation in the case of agro-environnemental management plans (e.g. like in Bonnieux et al., 2004; Ducos et Dupraz, 2007; Grolleau et al., 2007).

5.3. Innovative systems for banana cultivation in the FWI

We consider in this paper five alternative agricultural systems for banana production in the FWI, each system involving different technological innovations that are currently under development. The first one consists in intercropping banana with a leguminous cover crop and no herbicide. The second consists in adopting new banana hybrid plants that are tolerant to pests and neither fungicide nor nematicide. The third consists in improved fallow and to stop nematicide use for 3 years after banana plantation. The fourth innovative system is an integrated system combining improved fallow and intercropping, a reduction in nematicide use, and no herbicide. The fifth system is an organic banana production system with intercropping, improved fallow, organic fertilization, and no chemical inputs. Note that the second and the fifth innovations are particular, as they would allow banana to be sold at a higher price because of their organic or new nature. Banana fruits produced from new hybrids are new products: they are much smaller in size, have a different taste, and they are produced with a reduced and reasoned use of pesticide. For these new characteristics, this kind of banana would make it possible to be sold at a 50% higher price. Banana produced according to system 5 is a conventional Cavendish cultivar of banana but can be sold on organic markets due to the total avoidance of pesticide use. It could be sold at a 20% higher price. All of these systems allow farmers to reduce pesticide use, but they also include modified practices not directly associated with the use of that input (e.g., modified fallow, intercropping).

To test for the influence of incentive-driven attributes on adoption, we chose to design a survey whose purpose is to help identifying stated preferences. The alternative approach of identifying revealed preferences (that is, preferences identified through production or investment decisions by farmers) is not feasible in our case, as the list of innovations above has been rarely considered before by farmers. In this sense, our approach is almost entirely an *ex ante* one. However, to make farmers familiar with the vector of payment if the innovative agricultural systems were to be implemented, we propose them to farmers as agro-environmental measures. Hence, only the “contents” of the measures may change compared to their existing practices, but not the way they are compensated when adopting. Farmers are already familiar with public compensatory schemes (in particular, those related to rural development policies of the European Commission). Farmers are therefore likely to receive compensatory payments when signing a contract with the State which involves the adoption of new agricultural practices (pesticide reduction in our case).

The survey questionnaire was administrated through a single face-to-face interview to 607 farmers, 168 from Guadeloupe and 439 from Martinique, with a sampling rate of about 80% in each island. Farmers were asked if they would adopt any of the 5 innovations presented, given their technical and economic situation. Innovation was considered divisible, as farmers could decide to adopt innovations only on a part of the farm land. Surveyors were trained to provide all entailed explanations on the innovations to well describe them to farmers in a generic and homogenous way. All interviews were conducted between March and June 2008.

Category	Variables	Definition	Units
Innovation attributes: nature and performance	I1	Intercropping and no herbicide	0 1
	I2	New banana hybrid, neither fungicide nor nematicide	0 1
	I3	Improved fallow and reduction in nematicide use	0 1
	I4	Improved fallow, intercroping, no herbicide and reduction in nematicide use	0 1
	I5	Improved fallow, intercroping, organic fertilization, no chemical inputs	0 1
	INCOME	Net income from banana	€ ha^{-1} yr^{-1}
	PESTICIDE	Amount of pesticide active matter used per year	kg ha^{-1} yr^{-1}
	PRODUCTIVITY	Average banana yield	t ha^{-1} yr^{-1}
	WORK	Amount of work at field and for packaging banana	d ha^{-1} yr^{-1}
Policy and market attributes	BAN_PRICE	Increase in banana sale price	%
	DURATION	Contract duration for green subsidy and innovation adoption	yr
	SUBSIDY	Subsidy associated with innovation adoption	€ ha^{-1} yr^{-1}
Farmer socio-demographic characteristics and personal attitudes	AGE	Age of the farmer	Years
	ANTICIP_FUT_SUBS_DEC	1 if farmer anticipates that subsidies to production will decrease	0 1
	ANTICIP_FUT_ECO_MARK	1 if farmer anticipates that banana ecolabelled markets will be accessible	0 1
	ANTICIP_PRICE	1 if farmer anticipates that banana price is going to decrease	0 1
	ANTICIP_REGULATION	1 if farmer anticipates that all pesticides will be prohibited	0 1
	ATTITUDE_EARLY_ADOPTER	1 if farmer will instantly try an innovation if it becomes available	0 1
	ATTITUDE_FOLLOWER_ADOPTER	1 if farmer prefers to see innovation adopted before trying it	0 1
	ATTITUDE_LAGGARD_ADOPTER	1 if farmer prefers innovation being widely adopted before trying it	0 1
	AVERSION_CHANGE	1 if farmer would not adopt if he has to change his practices significantly	0 1
	HIGH_EDUC	1 if farmer has a higher education degree	0 1
	OBJ_DIVERSIFICATION	1 if farmer wishes to diversify its production	0 1
	OBJ_LAND_INCREASE	1 if farmer wishes to increase his farm land area	0 1
	OBJ_STABILIZATION	1 if farmer wishes to stabilize his technical management of banana	0 1
	OBJ_TON_INCREASE	1 if farmer wishes to increase its production	0 1
	SEX	1 if farmer is a male	0 1
Farm constraints and structure	CASHFLOW_LIMIT_OFTEN	1 if farmer is often limited by lack of cash flow	0 1
	CASHFLOW_LIMIT_PERMANENT	1 if farmer is permanently limited by lack of cash flow	0 1
	CASHFLOW_LIMIT_SELDOM	1 if farmer is seldom limited by lack of cash flow	0 1
	CREDIT_ACCESS	1 if farmer has access to credit	0 1
	DEBT	1 if farmer has on-going debt or loan	0 1
	DEPENDENCE_BANANA	Proportion of farmer's income provided by banana	%
	FAMILY_WORK	Proportion of family labour force	%
	GOOD_BAN_INCOME	1 if banana production allows to satisfy the needs of the farmer’s household	0 1
	IRRIGATION	Proportion of banana fields under irrigation	%
	LAND	Farm land area	ha
	NONFLEXIBLE_MANPOWER	1 if farmer has no possibility for managing an increase in workload	0 1
	OFF_FARM_WORK	1 if farmer is part-time farmer and has other job	0 1
	SLOPE	1 if average slope of bananas’ field is greater than 20%	0 1
	TEMPORARY_WORK	% of part-time labour employed	%
Geographical, institutional, social and economic context	INFORM_FARMER	1 if farmer contacts other farmers in case of technical problem	0 1
	INFORM_RESEARCH	1 if farmer contacts research agents in case of technical problem	0 1
	INFORM_UNION	1 if farmer contacts producer union advisors in case of technical problem	0 1
	MARTINIQUE	1 if farmer is in Martinique, 0 for Guadeloupe	0 1

Table 1. Definition of variables

Table 1 describes the variables selected to model innovation adoption in banana production in the FWI. 45 factors were considered to cover the five categories mentioned above. The choice of the factors has been made according to those found in the literature on adoption, while adapting them to the specificities of the innovations in banana production and of the local context of the FWI. Factors to describe farmers' expectations were likely to be subject to market and policy changes, such as the sale price for banana, pesticide regulation, and public subsidy policies for agriculture. Four variables allow us to describe the farmer's strategic objectives for her farm: land increase, production increase, technical stabilization, and product diversification. Variables representing constraints at the farm level were relative to work and cash flow limitations, as these limitations are allegedly important in the FWI (Bonin and Cattan, 2006, Cattan and Dulcire, 2002). As a consequence, the choice of innovation attributes was made dependent on critical production determinants in FWI, namely labour, the level of income, pesticide use and banana production.

As the performance of innovations can differ greatly among farmers due to variations in the environmental and economic context, the latter were calculated with the help of a bio-economic farm model. This model is based on a farm typology which is representative of FWI banana growers, and all technical and economic parameters were calibrated using a survey on a sample of 10% of banana farms (Blazy et al., 2008a, 2008b).

This typology reveals clear differences among farm types in terms of spatial location, economic characteristics, and actual economic and technical performance. For the purpose of the present study, the typology has been simplified according to two factors only: farm size and altitude, as they were found to be the major discriminating factors of the variability of biophysical and economic situations. On the one hand, farm size is indeed associated with a better access to water, a higher level of mechanization, and proper financial capacities. On the other hand however, farm size is associated with higher labour costs. Altitude is also important as it is associated with situations where mechanization is difficult and rainfall and solar radiation are more important. We distinguish 3 categories (clusters) of farms: A (< 15 ha and altitude < 250m), B (> 15 ha), and C (< 15 ha and altitude > 250m).

Economic and policy attributes to promote innovation adoption are the level of compensatory payment, duration of the contract, and banana's sale price. Compensatory payments were designed using two objectives: to compensate farmers for income loss and to encourage adoption in proportion of the reduction in pesticide use. Contract durations were mainly determined by the need to ensure technical consistency from an agro-environmental point of view. The expected impact on banana's sale price for innovations 2 and 5 was specified in the survey following interviews with marketing agents from the union of producers, respectively a 50% increase and a 20% increase.

Farm Type	Innovation's technical nature	Impact on production	Impact on banana sale price	Impact on workload	Impact on pesticide use	Income change (€/ha/an)	Subsidy (€/ha/an)	Contract duration (years)
A	I1 : intercropping banana with leguminous	+10%	=	+50%	-30%	-1600	2100	3
	I2 : new hybrids	-40%	+50%	-15%	-70%	+800	1000	6
	I3 : improved fallow	+55%	=	+25%	-30%	+6600	500	5
	I4 : intercropping and improved fallow	+50%	=	+55%	-60%	+4200	900	5
	I5 : organic banana production	+70%	+20%	+100%	-100%	+11000	1500	9
B	I1 : intercropping banana with leguminous	+4%	=	+30%	-30%	-2100	2600	3
	I2 : new hybrids	-45%	+50%	-10%	-70%	-1000	2000	6
	I3 : improved fallow	+2%	=	+5%	-15%	+1600	200	5
	I4 : intercropping and improved fallow	+1%	=	+25%	-60%	-1200	2100	5
	I5 : organic banana production	+5%	+20%	+60%	-100%	+4700	1500	9
C	I1 : intercropping banana with leguminous	+25%	=	+45%	-55%	-400	1200	3
	I2 : new hybrids	-35%	+50%	-10%	-20%	+600	300	6
	I3 : improved fallow	+10%	=	=	-25%	+1700	400	5
	I4 : intercropping and improved fallow	+10%	=	+25%	-100%	+150	1500	5
	I5 : organic banana production production	+50%	+20%	+80%	-100%	+4400	1500	9

Farm type A = farm size < 15 ha and altitude < 250m,
Farm type B = farm size > 15 ha,
Farm type C = farm size < 15 ha and altitude > 250m.

Table 2. Innovation and policy attributes for the different farm types

Table 2 summarizes the way innovations were presented to farmers during the interview, according to their specific farm type defined above. We can see that the impact of innovations varies considerably among farm types, hence showing the interest of a preliminary conjoint use of a bio-economic farm model and of a farm typology to identify more accurately innovation attributes. A variable to measure the level of credibility accorded by farmers to these scenarios was also part of the questionnaire.

5.4. The model of adoption

We build in this section a simple adoption model for a representative farmer, facing the choice of adopting an innovative production technology or keeping a traditional one. Let *j* index production technology, where *j=0* (respectively *j=1*) represents the traditional (respectively, the innovative) technology. Let

$$(1) \qquad U_j = U(\Pi_j = pq - rX); q = F_j(X); G_j(X;Z) \geq 0, \; j = 0,1,$$

denote the utility of profit under technology *j*, where *p* denotes output price, *X* is the vector of variable inputs, *r* is the corresponding vector of unit vector prices, $F_j(g)$ is the production function, and $G_j(gg)$ represents the feasible production set. Note that the latter includes not only technical constraints on production, but also regulatory constraints depending on exogenous variables *Z*. When making a decision, the farmer is assumed to account for uncertainty associated with future output price, climate risk, future environmental regulation, and random access to some production inputs. For example, regulation on pesticide use or access to inputs such as capital and labour are likely to affect the farmer differently whether he adopts the innovative technology. Similarly, random climatic conditions will result in expected crop yield differentials whether the traditional technology or the innovation is chosen. On the other hand, future crop prices will have the same impact on sales conditional on output, irrespective of the technology. Note that we implicitly make the assumption that input prices are deterministic, although access to some inputs is indeed random.

Assume the farmer exhibits some degree of risk aversion, so that the utility function *U(.)* is increasing and quasi-concave in profit. Uncertainty on future prices, environmental regulation and access to inputs results in the following programme to be solved by the farmer:

$$(2) \qquad \max EU\left[\Pi_j = p\left(\varepsilon_p\right)F_j(X,\varepsilon_q) - rX\right] + \lambda\left[EG_j(X,Z,\varepsilon_Z)\right]$$

if technology *j* is selected, where *E(.)* is the expectation operator over random terms $(\varepsilon_p, \varepsilon_q, \varepsilon_Z)$, affecting output price, crop yield and exogenous (to the farmer) constraints.

The solution to programme (2) is denoted $EU_j, j = 0,1$, and depends in a non-trivial fashion on the distribution of random shocks $(\varepsilon_p, \varepsilon_q, \varepsilon_Z)$, farmer preferences (through the utility function) and exogenous variables such as input prices and *Z*. Since expected utility can be written as the sum of a certainty equivalent and the risk premium, the decision rule of the farmer will be:

(3) Adopt technology j if $EU_j = CE_j + RP_j > EU_0 = CE_0 + RP_0$,

where CE_j and RP_j respectively denote the certainty equivalent and the risk premium. Assume further that certainty equivalent depends on a set of observed variables *W* and on an observed heterogeneity, technology-specific random term θ_j, namely $CE_j = \mu_j(W) + \theta_j$. θ_j represents the idiosyncratic component of the certainty equivalent, assumed uncorrelated with variables *W*. Similarly, the risk premium is assumed to depend on variables *V* characterizing uncertainty associated with technology, in the sense introduced above, so that $RP_j = \varphi(V_j)$. Typically, variables *W* would be farmer-specific while *V* would depend both on technology and on the farmer. Equation (3) then becomes

(4) Adopt technology j if $\mu_j(W) - \mu_0(W) + \varphi(V_j) - \varphi(V_0) \; > \; \theta_0 - \theta_j$.

The decision to adopt the innovative technology is then seen to depend on the location of a non-random difference between certainty equivalents and risk premiums, with respect to the difference in the technology-associated heterogeneity. Trivially, for a risk-neutral farmer, equation (4) would reduce to the comparison between the expected profit levels associated with technology 0 and *j*. Models like the one given in equation (4) is typically not identified with any choice of functional forms μ and φ. A common procedure is to assume linearity of those functions, which yields the final adoption model:

(5) Adopt technology j if $W\left(\delta_j - \delta_0\right) + (V_j - V_0)\eta \; > \; \theta_0 - \theta_j$,

where variables V_j are technology-specific variables and *W* depend on the farmer only, δ and η are parameters.

The econometric estimation procedure consists in estimating equation (5) with a parametric binary-choice model, using farmer-specific and technology-related explanatory variables. As multiple (non exclusive) answers are allowed in the survey, farmers may report several innovations simultaneously. As a result, the sample can be considered similar to a "panel" dataset in which each farmer is represented more than once (as much as there are innovations), introducing the need to control for farmer-specific heterogeneity across observations. As we will see below, we account for a farmer systematic effect by incorporating observed variables only.

The probability for farmer *i* to adopt an innovative technology *j* is

(6) $$\Pr(y_{ij}=1)=\Pr\left[W_i\left(\delta_j-\delta_0\right)+(V_{ij}-V_{i0})\eta>\theta_{i0}-\theta_{ij}\right]=\Pr\left[W_i\delta_j^*+V_{ij}^*\eta>\omega_{ij}\right].$$

The probability of adoption reads $G\left(W_i\delta_j^*+V_{ij}^*\eta\right)$, where *G(.)* is the cumulative density function of ω_{ij}. Combining probabilities of adoption across innovations for the same farmer forms the basis of the maximum-likelihood estimation procedure:

(7) $$\max_{(\delta,\eta)}\log L(y|x,\delta,\eta)=\sum_{i=1}^{N}\log\left[l_i\left(y_i|x_i,\delta,\eta\right)\right]=\sum_{i=1}^{N}\log\left[\Pr\left(y_i|x_i,\delta,\eta\right)\right],$$

where $y_i=(y_{i1},y_{i2},\ldots,y_{iM})'$, $x_i=(x'_{i1},x'_{i2},\ldots,x'_{iM})'$ and l_i is the joint probability of the *M* vector y_i, with *M* the number of innovations. Assuming parameters are constant across innovations leads to a binary-choice Logit or Probit model. In this case, farmer-specific heterogeneity is captured through variables W_i and innovation-farmer heterogeneity through variables V_{ij} only. We estimate the probability of adoption by a binary Logit model, under the implicit assumption that, conditional on farmer characteristics (and innovation attributes), the probabilities of adoption are independent across innovations.

5.5. Estimation results

5.5.1. Adoption rates and population characteristics

Innovation	**Island**	**Adoption rate (percent)**
I1: Intercropping banana with leguminous crops	Guadeloupe	76
	Martinique	55
	Total	61
I2 : New hybrids	Guadeloupe	59
	Martinique	51
	Total	53
I3 : Improved fallow	Guadeloupe	72
	Martinique	65
	Total	67
I4: Intercropping and improved fallow	Guadeloupe	66
	Martinique	56
	Total	59
I5/ Organic banana production	Guadeloupe	30
	Martinique	43
	Total	39

Table 3a. Adoption rates according to the island

Table 3a presents the adoption rates of the innovations as obtained in the survey. Adoption rates vary from 39% for organic banana production (I5) to 67% for improved fallow (I3), the overall average adoption rate being 56%. It is interesting to see that innovation I4, which could technically be seen as the union of I1 and I3, has an adoption rate just below individual innovations of I1 and I3 (59% against 61% and 67%). Adoption rates are similar in the two islands (Martinique and Guadeloupe) for 3 innovations but it is interesting to note that the adoption rate of intercropping (innovation I1) is considerably lower in Martinique while this is the opposite for organic banana production.

Table 3b presents the descriptive statistics of the variables used in this study. The phenomena that farmers expect as the most likely are pesticide regulation and opening of an accessible eco-labelled banana market. 50% of farmers declared themselves as 'early adopter', 26% as 'follower adopter' and 20% as 'late beginner' (4% declared themselves totally reluctant to innovation in general). These results reveal the relative importance for a farmer of being seen as an 'innovator' in explaining adoption. As concerns farmers' objectives, 53% of farmers in the sample declared themselves as looking for alternatives farming systems, while 39% declared trying to stabilize their technical management of banana production. 58% of farmers seek to increase their banana production yield. This makes sense in the face of the average yield in the sample being rather low compared to banana potential (26 ton per hectare per year, compared to a maximum possible output of about 55 ton).

It is interesting to note that 42% of farmers report a frequent lack of cash flow, while 71% claim that they would have difficulties in managing an increase in work load. Only 18% of farmers declare themselves as having a "correct" income from banana production, while dependence to banana is very high, as it represents on average 90% of income. Concerning the source of (technical) information, 96% of farmers are in contact with a producer union in case of a problem, while only 16% declare to be in contact with research and development agents. Only 55% of farmers would ask other farmers for assistance in case of a problem. Finally, the level of credibility given to attributes in our scenarios was assumed to be satisfying, with a rate of 88%.

Category	Variables	Mean	Standard-deviation
Farmers socio-demographic characteristics and personal attitudes	AGE	48.71	9.67
	ANTICIP_FUT_SUBS_DEC	0.31	0.46
	ANTICIP_FUT_ECO_MARK	0.76	0.43
	ANTICIP_PRICE	0.36	0.48
	ANTICIP_REGULATION	0.50	0.50
	ATTITUDE_EARLY_ADOPTER	0.50	0.50
	ATTITUDE_FOLLOWER_ADOPTER	0.26	0.44
	ATTITUDE_LAGGARD_ADOPTER	0.20	0.40
	AVERSION_CHANGE	0.32	0.47
	HIGH_EDUC	0.24	0.43
	OBJ_DIVERSIFICATION	0.53	0.49
	OBJ_LAND_INCREASE	0.22	0.42
	OBJ_STABILIZATION	0.39	0.49
	OBJ_TON_INCREASE	0.58	0.49
	SEX	0.88	0.32
Farm's constraints and endowments	CASHFLOW_LIMIT_OFTEN	0.42	0.49
	CASHFLOW_LIMIT_PERMANENT	0.09	0.28
	CASHFLOW_LIMIT_SELDOM	0.24	0.43
	CREDIT_ACCESS	0.48	0.50
	DEBT	0.47	0.50
	DEPENDENCE_BANANA	0.90	0.21
	FAMILY_WORK	0.50	0.39
	GOOD_BAN_INCOME	0.18	0.38
	IRRIGATION	0.30	0.41
	LAND	10.85	19.20
	NONFLEXIBLE_MANPOWER	0.71	0.45
	OFF_FARM_WORK	0.10	0.30
	SLOPE	0.18	0.39
	TEMPORARY_WORK	0.27	0.32
Geographical, institutional, social and economic context	INFORM_FARMER	0.55	0.50
	INFORM_RESEARCH	0.16	0.37
	INFORM_UNION	0.96	0.19
	MARTINIQUE	0.72	0.45

Notes. 607 observations.

Table 3b. Descriptive statistics of explanatory variables relative to farmer, farm and policy context.

5.5.2. The determinants of adoption

Table 4 presents the results of the binary Logit estimates, based on maximizing the log-likelihood (7) above. We can see that both significant and non significant adoption determinants are present in each category of variables. BANANA'S PRICE, PESTICIDE and DURATION are the only attributes that influence significantly innovation adoption. However, SUBSIDY plays a significant positive role when introduced in interaction with ANTICIP_FUT_SUBS_DEC.

It is interesting to see that PESTICIDE and DURATION play an opposite role when they are combined with two other expectation variables, compared with their own direct effect. The coefficient on BAN_PRICE is affected when combined to ANTICIP_FUT_ECO_MARK, as the parameter is smaller in absolute value compared to the direct effect of the variable. These results show that farmers' expectations play an important role in the decision to adopt. The technical nature of innovations and the geographical context captured by the location in one of the two FWI islands interact in a significant way for two of the five innovative systems (I1 and I5).

Farmer's socio-demographic characteristics do not significantly influence the adoption of innovation (AGE, HIGH_EDUC and SEX). Variables related to farmers' attitudes are highly significant: attitude toward innovation, aversion to change and personal objectives all influence significantly the willingness to adopt an innovation. Objective "farm diversification" influences adoption in a positive way, which is rather surprising but could be explained by the fact that farmers wishing to diversify their production are looking for alternative crop systems and could be interested in other ways of producing banana that could open new markets. OBJ_LAND_INCREASE impacts adoption negatively, which could be explained by the presence of improductive fallows in 3 of the 5 innovations (I3, I4 and I5). OBJ_STABILIZATION negative effect is not significant.

Cash flow constraints clearly play a surprising and positive role. It could be explained by the fact that, at a strategic level, the more constrained the farmer, the more he is likely to adopt low input innovations that could allow him to save on inputs, thereby improving his level of cash flow.

Category	Parameter	Estimate	t-statistic
Innovations' attributes : nature and performances	INCOME	-6.386 E-6	-0.21
	PESTICIDE	0.0257**	2.63
	PRODUCTIVITY	-0.0116	-1.40
	WORK	0.1052	0.47
Policy and market attributes	BANANA'S PRICE	-0.1447**	-2.46
	DURATION	-0.3166***	-5.23
	SUBSIDY	1.22E-4	1.08
Interaction terms	BAN_PRICE*ANTICIP_FUT_ECO_MARK	0.1702***	4.27
	DUR*ANTICIP_PRICE	-0.0759***	-5.00
	SUBSIDY*ANTICIP_FUT_SUBS_DEC	1.11E-4*	1.70
	WORK*NONFLEXIBLE_MANPOWER	-0.2455	-1.26
	INCOME*GOOD_BAN_INCOME	4.31 E-5*	1.80
	PESTICIDE*ANTICIP_REGULATION	-0.0326***	-3.68
	PRODUCTIVITY*OBJ_TON_INCREASE	0.0114	1.58
	I1*MARTINIQUE	-0.9788	-4.74
	I2*MARTINIQUE	0.0054	0.03
	I3*MARTINIQUE	0.4966***	2.68
	I4*MARTINIQUE	0.0237	0.14
	I5*MARTINIQUE	0.8017***	3.74
Farmers socio-demographic characteristics and personal attitudes	AGE	-0.0068*	-1.66
	ATTITUDE_EARLY_ADOPTER	1.4912***	6.29
	ATTITUDE_FOLLOWER_ADOPTER	1.0289***	4.34
	ATTITUDE_LAGGARD_ADOPTER	0.9488***	3.83
	AVERSION_CHANGE	-0.8675***	-9.77
	HIGHER_EDUC	0.1105	0.93
	OBJ_DIVERSIFICATION	0.4711***	5.15
	OBJ_LAND_INCREASE	-0.3514***	-3.29
	OBJ_STABILIZATION	-0.0696	-0.74
	SEX	0.1339	1.01
Farm constraints and structure	CASHFLOW_LIMIT_OFTEN	0.2697**	2.39
	CASHFLOW_LIMIT_PERMANENT	0.5883***	3.29
	CASHFLOW_LIMIT_SELDOM	-0.1164	-0.95
	CREDIT_ACCESS	0.3762***	3.97
	DEBT	-0.3230***	-3.41
	DEPENDENCE_BANANA	0.9445***	4.51
	FAMILY_WORK	-0.1626	-1.24
	IRRIGATION	-0.4618***	-3.86
	LAND	-0.0034	-1.20
	OFF_FARM_WORK	-0.1495	-0.93
	SLOPE	-0.3436***	-3.00
	TEMPORARY_WORK	0.2984**	2.19
Geographical, institutional, social and economic context	INFORM_FARMER	-0.2500***	-2.78
	INFORM_RESEARCH	0.4771***	3.35
	INFORM_UNION	0.5048**	2.49

Notes. 607 observations, 5 innovations. Likelihood Ratio test statistic $\chi^2(44) = 676.57$ (p-value=0.0000). Log likelihood = -1671.8403. Pseudo-R^2 = 0.1683. *, ** and *** respectively denote parameter significance at the 10, 5 and 1 percent level.

Table 4. Binary Logit estimates

However, adoption is affected negatively by poor access to credit and high level of debt (positive parameter on CREDIT_ACCESS and negative parameter on DEBT), which shows that at a tactical level financial limitations could affect negatively adoption. Constraints relative to work load were expected to be important, but they are not significant (coefficient on WORK*NONFLEXIBLE_WORK). However, the presence of temporary workers on the farm seems to favour adoption, maybe because it allows for more flexibility in the management of intra-seasonal changes work requirements. Estimated parameters on variables related to farmer's sources of information revealed that access to research and farmer union technical agents play a positive role on adoption.

5.5.3. Marginal effects and elasticities

Marginal effects of the binary explanatory variables in the conditional Logit model are presented in **Table 5a.** They are computed as the difference $\Pr(y=1|X=1)-\Pr(y=1|X=0)$. These results confirm the role of interactions between the nature of innovations on the one hand and the geographical context on the other. According to our results, the probability of adoption of I1 is reduced by 23.7% for farmers in Martinique, while the adoption rate of I5 would be 19.7% higher for the same island. Being an "early adopter" yields a higher probability of adoption by about 12% compared to being a "follower" or a "late-beginner". Marginal effects of these two variables are very comparable (24.2% compared with 22%), which shows that these two determinants only allow to discriminate, on the one hand farmers who need to see an innovation implemented in other farms before deciding to adopt it, and on the other hand, farmers who are very reluctant to change their production system. The marginal effect of risk aversion is indeed consistent with these results, because the effect of variable AVERSION_CHANGE reveals that being averse to change reduces adoption probability by 21%.

Estimates for variables related to farmers' objective show that when farmers are looking for more farm land, adoption probability decreases by 8.8%, confirming the way scarcity of land in these small Caribbean islands can limit adoption of innovation. Cash flow constraints increase adoption probability by 6.5 to 14.2%, showing the strategic interest of low input systems for farms that are subject to a chronic lack of cash flow.

Category	Parameter	dy/dx	t-statistic
Island x innovation dummy	I1*MARTINIQUE	-0.237***	-4.06
	I2*MARTINIQUE	-0.011	-0.21
	I3*MARTINIQUE	0.107**	2.39
	I4*MARTINIQUE	-0.008	-0.21
	I5*MARTINIQUE	0.197***	3.91
Farmers socio-demographic characteristics and personal attitudes	ATTITUDE_EARLY_ADOPTER	0.350***	6.43
	ATTITUDE_FOLLOWER_ADOPTER	0.242***	4.36
	ATTITUDE_LAGGARD_ADOPTER	0.220***	3.85
	AVERSION_CHANGE	-0.210***	-6.45
	HIGH_STUDY	0.029	1.03
	OBJ_DIVERSIFICATION	0.114***	5.16
	OBJ_LAND_INCREASE	-0.088***	-3.24
	OBJ_STABILIZATION	-0.016	-0.71
	SEX	0.029	0.9
Farm constraints and structure	CASHFLOW_LIMIT_OFTEN	0.065**	2.33
	CASHFLOW_LIMIT_PERMANENT	0.142***	3.39
	CASHFLOW_LIMIT_SELDOM	-0.032	-1.06
	CREDIT_ACCESS	0.098***	4.19
	DEBT	-0.083***	-3.54
	OFF_FARM_WORK	-0.028	-0.75
	SLOPE	-0.096***	-3.47
Geographical, institutional, social and economic context	INFORM_FARMER	-0.062***	-2.84
	INFORM_RESEARCH	0.123***	3.69
	INFORM_UNION	0.120**	2.22

Notes. Marginal effects in the case of binary explanatory variables are computed as Prob(Y | X=1) Prob(Y | X=0). *, ** and *** respectively denote parameter significance at the 10, 5 and 1 percent level.

Table 5a. Marginal effects (discrete explanatory variables).

Constraints related to debt and lack of access to credit have the similar effect of decreasing adoption probability by 8 to 10%. Access to informations and technical advice from research agents increase adoption probability by 12.3%, while having other farmers as a source of information in case of technical problem decreases adoption probability by 6%.

The impact of continuous variables is then assessed by computing elasticities of adoption probability with respect to these explanatory variables (**see Table 5b**). A 10% decrease in pesticide use decreases adoption probability by 1.2%, which shows that a tradeoff has to be found beetween pesticide reduction and adoption rate for most environmentally friendly systems. However, the elasticity of adoption probability with respect to variable PESTICIDE*ANTICIP_REGULATION indicates that a 10% decrease in pesticide use would increase adoption probability by 0.8% for farmers who anticipate a ban on pesticides.

Category	Variable	Elasticity	*t*-statistic
Interaction terms	BAN_PRICE*ANTICIP_FUT_ECO_MARK	0.718***	2.6
	DUR*ANTICIP_PRICE	-0.041***	-2.72
	INCOME*GOOD_BAN_INCOME	0.025	1.48
	PESTICIDE*ANTICIP_REGULATION	-0.078**	-2.39
	PRODUCTIVITY*OBJ_TON_INCREASE	0.094	1.48
	SUBSIDY*ANTICIP_FUT_SUBS_DEC	0.012	1.58
	WORK*NONFLEXIBLE_MANPOWER	-0.103	-1.29
Innovation attributes	INCOME	-0.021	-0.22
	PESTICIDE	0.122**	2.1
	PRODUCTIVITY	-0.167	-1.14
	WORK	0.051	0.44
Policy and market attributes	BANANA'S PRICE	-0.814	-1.44
	DURATION	-0.488***	-3.76
	SUBSIDY	0.038	0.99
Farmer socio-demographic characteristics and personal attitudes	AGE	-0.090	-1.47
Farm constraints and structure	DEPENDENCE_BANANA	0.260***	2.88
	FAMILY_WORK	-0.010	-0.57
	IRRIGATION	-0.034**	-2.5
	LAND	-0.009	-1.01
	TEMPORARY_WORK	0.025**	2

Notes. Elasticities in the case of continuous explanatory variables are computed as ∂Prob(Y | X) / ∂Prob(Y | X) x (X / Prob(Y)). *, ** and *** respectively denote parameter significance at the 10, 5 and 1 percent level.

Table 5b. Elasticities (continuous explanatory variables).

The elasticity with respect to DURATION is -0.488, which means that a 10% increase in the contract duration would decrease by 4.9% the probability of adoption. This value is reduced by as much as ten times to 0.4% for farmers who anticipate a decrease in banana price. Increasing by 10% the price of banana sale would decrease adoption probability by 8.1% but would increase adoption probability by 7.2% for farmers who believe in the opening of new eco-labelled markets.

5.6. Discussion, policy and agronomic recommendations

Table 6 presents the predictive performance of the binary Logit model of adoption. Although the model’s Pseudo-R^2 is low (0.16), the average percentage of correct predictions is 70.14% which is correct for this type of survey-based econometric experiment. Our model tends to overestimate adoption except for innovation I5, where it predicts 4% less adoptions. There are no significant differences across innovations, with a correct prediction rate beetween 66% and

74%, which confirms the relative goodness of fit of the model as its predictive capacity is independent from the nature of innovation. However, we assume that the predictive ability of the model could be improved by introducing more interaction terms between innovation's features and farmer's or farm's characteristics.

Innovation	Observed dependent variable	Predicted outcome 0	Predicted outcome 1	Percentage of correct predictions	Average percentage of correct predictions
1	0	21.74%	17.46%	74.29%	70.14%
	1	8.23%	52.55%		
2	0	28.83%	18.28%	66.39%	
	1	15.32%	37.56%		
3	0	12.19%	21.08%	69.35%	
	1	9.55%	57.16%		
4	0	23.88%	17.29%	73.79%	
	1	8.89%	49.91%		
5	0	46.45%	14.49%	66.87%	
	1	18.61%	20.42%		

Table 6. Predictive performance of the binary Logit model

This study was the first adoption study ever made in the French West Indies. Applied to banana growers, it allowed us to highlight *ex ante* the role of several determinants influencing stated farmer decision to adopt innovative, low-input banana management systems for banana production, presented to farmers with differentiated innovation and policy attributes. Results show that only 3 of the 7 attributes influence adoption decisions. Pesticide reduction plays a negative role on adoption, particularly for farmers who do not anticipate a ban on pesticides. According to identified farmer's stated preferences, an appropriate policy for supporting innovation adoption should avoid contracts with a too long duration. This can be explained by the poor visibility of farmers about the future of banana production in the FWI. Another level of policy action could be located at the supply chain level, by facilitating and promoting the access of FWI banana's production to new eco-labelled banana's markets, which constitute a powerful incentive for innovation adoption. Low adoption rates of innovations whose economic success is based on higher banana's sale price (new hybrids and organic banana, I2 and I5) can be explained by the current poor access of farmers to these markets, hence the negative effect of attribute BANANA'S_PRICE. We have to underline the fact that this study show that signs and elasticities of innovations and policy attributes can be strongly affected by interactions with farmer's personal attitudes, in particular expectations on future environmental and agricultural policy, and economic outlook.

According to our results, constraints related to work management who were expected to limit adoption do not play a significative role. Financial constraints influence adoption in a peculiar and conflicting way: on the one hand, cash flow constraints make farmers more likely to adopt low-input innovations, but on the other hand, debt and lack of access to credit tend to limit adoptions. This result indicates that at a short and "tactical" horizon, farmers constrained by debt and poor access to credit would not be able to adopt innovations, whereas their chronic lack of cashflow would make them more likely to adopt innovations, but at a longer and strategic horizon. This shows the limit of our *ex ante* approach, based on stated preferences only, where farmers are only asked to report if "they would adopt", which can lead to the expression of different scales of thinking in farmer's decision, making thus the analysis more complex.

Our study highlighted the role of interactions beetween innovation features and the geographical context, as our adoption model shows that intercropping would be less adopted in Martinique while this is the contrary for organic production of banana. One geo-agronomic explanation to lower adoption of intercropping in Martinique could be suggested, by assuming that in this latter island, the presence of a dangerous snake (*Bothrops lanceolatus*) could make cover crops located in the passage zone of field operators problematic. One consequence of this result could be to identify less "cumbersome" cover crop, or new spatial configuration of intercropping in order to make safe the passage of field operators. As concerns organic banana, the observed different adoption rate could be explained by the much more important social pressure for a cleaner production in Martinique, because banana production is much more present in this island and is associated with the highly publicised problem of water and soil contamination. The presence of irrigation and high slope level plays a negative role on adoption, which can be linked to an increase in work arduousness in these situations, which has to be taken into account in the design of innovation.

Modelling jointly the adoption of five different innovations shows clearly that variables representing farmers' attitudes toward innovation and aversion to change seem to play a determinant role, which would suggest to bear further interest to socio-psychological determinants of innovation adoption. Farmer's main objectives for the strategic orientation of their farm can also play a considerable role, which can orient the agronomic nature of innovations. For example, taking into account the farmer's objective of increasing the size of their farm in a context of land scarcity, could result in orienting innovation design towards very short and productive banana rotations instead of non productive long improved fallow. Variables related to the source of information seem to play a considerable role too, in particular information provided by local research and extension. This could however be explained in part by our *ex ante* position which would make access to information on new and unknown innovations particularly crucial.

From a methodological point of view, the adoption study being an *ex ante* one, seems to lead naturally to give more focus on strategic determinants of adoption, and to make the assessment of another important dimensions of adoption more difficult, like speed and intensity of adoption and their determinants. Another limit of the method is that we model innovation adoption in a very limited framework in terms of policy and innovation attributes, but this was the price to pay to provide quantitative information on numerous innovations and policy attributes and thus to maximize the credibility of the scenarios, which can be a crucial point in an *ex ante* study. However, by allowing the assessment of a large set of adoption factors for different innovative systems, our methodology seems to be sufficiently robust and operational for proposing some relevant agronomic and policy recommendations to improve innovation design and to define relevant policy incentives.

5.7. Concluding remarks

Our *ex ante* adoption model applied to banana production in the FWI allowed us to identify the determinants affecting adoption of five innovative agro-environmental contracts involving technological innovations and incentives. Our estimation results show that interactions between farmer's related explanatory variables and innovation and policy attributes could strongly affect adoption. This study also highlighted the considerable role of policy attributes, innovation's technical nature, geographical context, farmer's expectations, personal attitudes and objectives, which permitted us to propose agronomic and policy recommendations for supporting innovation.

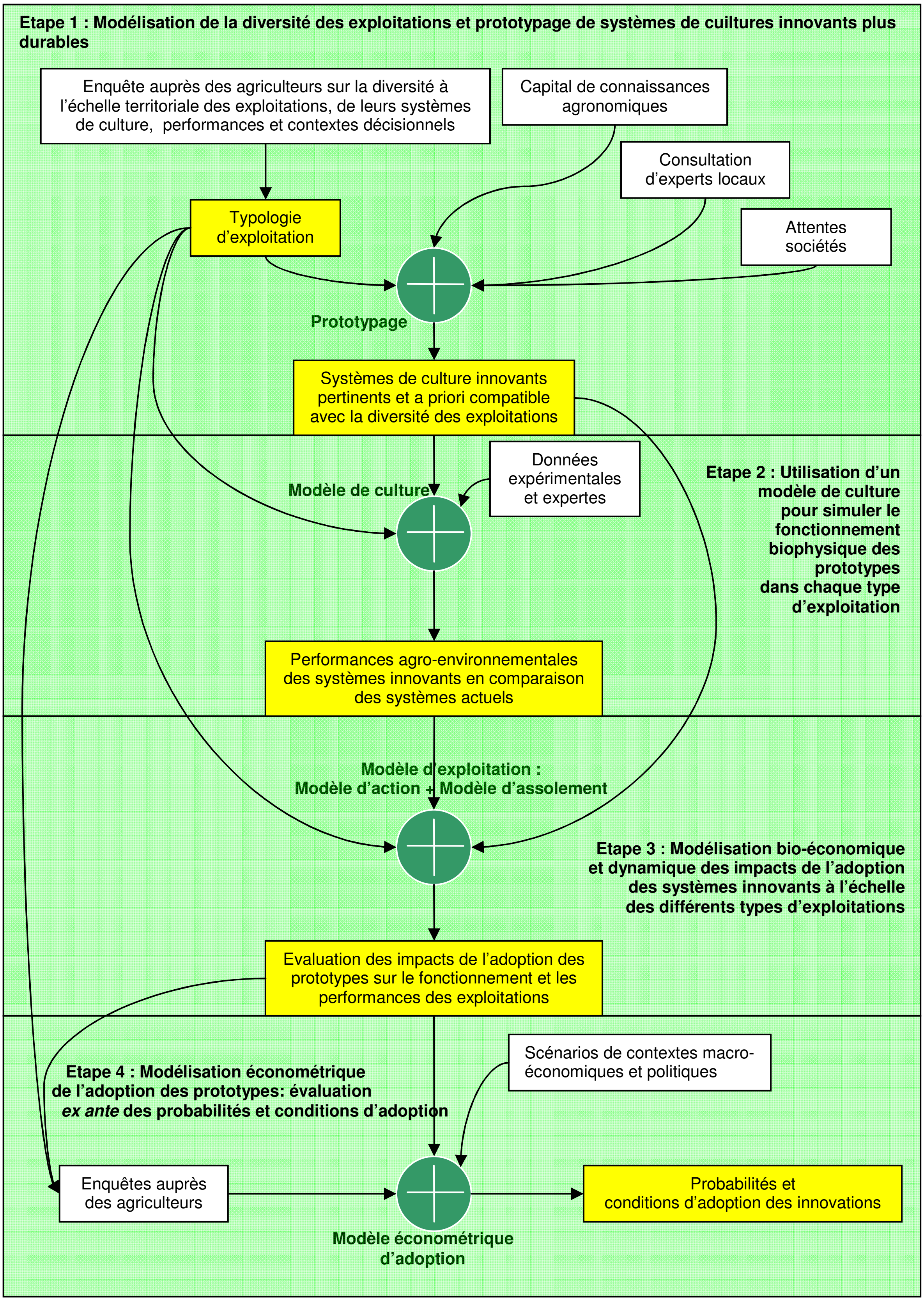

Figure E : proposition méthodologique pour l'évaluation *ex ante* de systèmes de culture innovants, de la conception à l'adoption, à l'échelle du territoire.

6. Discussion générale et perspectives

Ce dernier chapitre a 3 vocations :

1. Porter un regard critique sur la démarche élaborée dans le cadre de cette thèse en discutant de ses limites.

2. Evaluer l'apport scientifique du travail présenté dans ce document, la généricité de la méthode et proposer de nouvelles pistes de recherches méthodologiques en matière de conception et évaluation de systèmes de cultures innovants.

3. Formuler des recommandations agronomiques et économiques pour contribuer à l'amélioration de la durabilité des systèmes de culture bananiers Antillais. Ce paragraphe s'adresse aux agronomes concepteurs, aux économistes de l'innovation, aux planteurs, aux groupements de planteurs et aux décideurs des politiques locales. Il propose une liste d'actions qui seraient à entreprendre au vu des résultats de cette thèse.

6.1. Limites de notre approche

Les limites individuelles de chaque étape de notre approche ont été décrites en détail en discussion de chacun des chapitres 2 à 5. Avant d'évaluer les faiblesses de l'approche globale, nous rappellerons les principales limites de chaque étape (cf. figure E ci-contre) :

- Etape 1, modélisation de la diversité et prototypage de systèmes de culture innovants: poids des experts, absence de participation des agriculteurs

- Etape 2, utilisation d'un modèle de culture pour simuler le comportement biophysique des prototypes dans les types d'exploitation: évaluation du modèle SIMBA à faire sur certaines innovations, pas de prise en compte de la variabilité interannuelle du climat, pas de test de sensibilité des innovations à des saisons climatiques extrêmes,
- Etape 3, modélisation bio-économique des impacts des innovations sur le fonctionnement et les performances des exploitations : absence d'étude de sensibilité sur certains paramètres, évaluation du modèle sur 6 répétitions seulement, modèle peu convivial, pas de prise en compte des contraintes de planification du travail
- Etape 4, modélisation économétrique de l'adoption des prototypes: conditions d'adoption évaluées sur la base de préférences « déclarées », limites du plan d'expérience, et taux de prédictions incorrectes de 29%.

En dehors, des éléments mentionnés ci-dessus nous avons identifié 2 principales limites dans notre approche globale :

- Absence d'évaluation des phénomènes de propagation d'incertitude dans la chaine de modèles
- Evaluation de l'innovation à d'autres échelles, impliquant d'autres acteurs.

6.1.1. Absence d'évaluation des phénomènes de propagation de l'incertitude dans la chaine de modèles

Comme nous l'avons vu précédemment, chaque modèle possède une part d'incertitude inhérente à la faiblesse des procédures d'évaluation et à l'incertitude pesant sur certains paramètres ou variables d'entrée. Il est donc légitime de se demander quelle est la part d'incertitude pesant sur une variable finale de l'évaluation comme le revenu ou la probabilité d'adoption, compte tenu de l'incertitude en entrée de chaque modèle. Les questions sont du type : « Quelle est l'influence de l'incertitude pesant sur le paramètre de transfert hebdomadaire d'azote au sol de la légumineuse associée sur la probabilité d'adoption ? »
Bien qu'il conviendrait d'interroger des statisticiens sur ce point, on peut néanmoins penser que cela pourrait être réalisé au cas par cas, en conduisant des études de sensibilité en reprenant toute la chaîne de modèles. Ces questions sont par exemple très vives en modélisation hydrologique, où les processus modélisés sont souvent multi-échelles (McIntyre et Wheater, 2004 ; Butts et al., 2004 ; Schanz et Salhotra, 1992).

De plus il faudrait ensuite voir comment prendre en compte cette incertitude pour décider et définir des recommandations. Il faudrait alors se pencher sur des méthodes d'aide à la décision multicritères qui permettrait d'intégrer ces facteurs d'incertitude comme des indicateurs à prendre en compte.

6.1.2. Evaluation de l'innovation à d'autres échelles, impliquant d'autres acteurs

Comme cela a été souligné en introduction de cette thèse le cadre de cette évaluation est limité à l'exploitation, et ainsi nous n'avons pas abordé de processus à l'échelle territoriale tels que l'impact sur la qualité de l'eau dans le réseau hydrologique régional, les impacts sur les écosystèmes naturels, les impacts économiques sur l'ensemble de la filière, et la diffusion des innovations dans les réseaux sociaux. Néanmoins l'approche typologique qui permet de modéliser la diversité des situations techniques, biophysiques et économiques pourrait être un outil utile dans cette perspective, par exemple en l'intégrant dans des modèles multi-agents ou des modèles hydrologiques.

De plus, bien que nous ayons implicitement pris en compte les attentes de la société à travers le prototypage d'innovations visant une amélioration de la durabilité globale, nous avons uniquement réalisé notre innovation du point de vue de l'agriculteur. En effet les 5 critères principaux que nous avons retenus sont tous relatifs à l'échelle de l'exploitation (productivité, charge de travail, utilisation de pesticides, revenus de l'exploitation, et probabilité d'adoption). Pour pallier à ce problème, il aurait été intéressant d'intégrer notre base de données de critères simulés pour chaque type d'exploitation dans un outil d'aide à la décision multi-critère permettant de prendre aussi en compte les points de vue et les attentes d'autres acteurs comme les collectivités locales, les associations de consommateurs ou les décideurs publics. Cela aurait permis de répondre à des questions du type : Quelle innovation pour maximiser tel critère ? Quelle innovation pour répondre à tel problème à telle échelle (un type d'exploitation, un territoire)? Cela amènerait à s'intéresser aux méthodes d'aide à la décision multi-critère, qui ont été décrites par Sadok *et al.* (2008) comme étant adaptées à la réponse à ces questions. Il s'agirait de prendre en compte simultanément à travers un seul outil tous les critères qui agiraient soient comme des filtres soient comme des contributeurs à des critères plus agrégés, dont le poids pourrait varier en fonction de l'échelle à laquelle on se place et du poids que l'on donne à chaque critère. Cet outil pourrait être utilisé de manière interactive avec une large gamme d'acteurs (agriculteurs, associations de citoyens, groupements de producteurs, décideurs), ce qui ouvrirait la voie à une véritable co-évaluation, voire co-construction, d'innovations. On rejoint içi la « modélisation d'accompagnement » qui a été développée par le collectif COMMOD (Gurung *et al.*, 2006).

6.2. Portée scientifique du travail

6.2.1. Les objectifs ont-ils été atteints ?

Malgré les limites décrites précédemment on peut considérer que les objectifs fixés au chapitre 1 (pages 27 et 42) ont globalement été atteints :

- En mobilisant différents outils de modélisation issus de l'agronomie et des sciences économiques et sociales dans un seul cadre à caractère systémique nous avons proposé une méthode d'évaluation *ex ante* de systèmes de cultures innovants plus durables, de la parcelle à l'adoption par les agriculteurs à l'échelle d'un petit territoire agricole. Cette méthode a été formalisée de manière générique et son application à la Guadeloupe a montré sa faisabilité. Nous discuterons en section 6.3.3 de la généricité de la méthode.

- Nous avons dressé un état des lieux et caractérisé la diversité des situations existantes en mettant en exergue la cohérence des systèmes de cultures actuellement pratiqués avec les cadres décisionnels qui les déterminent.

- Nous avons mis en cohérence les éléments d'innovations en cours de développement avec la diversité des situations actuelles pour en faire des systèmes de cultures innovants *a priori* adaptés aux problèmes et contraintes des planteurs, et susceptibles d'améliorer la durabilité de leur exploitation (chapitre 2).

- Nous avons ensuite évalué *ex ante* et à l'échelle des exploitations quels seraient les impacts économiques, techniques, agronomiques et environnementaux de l'adoption des systèmes innovants, à différents pas de temps (chapitres 3 et 4).

- Nous avons évalué quelles sont les probabilités et conditions d'adoption des systèmes par les planteurs, à l'aide d'un modèle économétrique générique (chapitre 5).

- Cette analyse nous a finalement permis de formuler des recommandations aux différents acteurs impliqués dans le processus d'innovation (planteurs, chercheurs agronomes et économistes, groupements, décideurs publics) en vue d'éclairer leur choix dans le développement et l'adoption de systèmes plus durables (chapitre 6).

Au-delà, nous pensons que les outils produits (typologies et modèles) pourraient être réutilisés à l'avenir par les agronomes concepteurs et les agents du développement pour construire et évaluer voire co-construire et co-évaluer d'autres innovations.

6.2.2. Principaux résultats à caractère potentiellement générique

Dans cette section, nous avons essayé de synthétiser les résultats à caractère potentiellement générique que cette thèse a fournis :

- Il est important de prendre en compte la diversité des exploitations dans la conception et l'évaluation de systèmes innovants car :
    - Les problèmes de durabilité se déclinent de manière différente selon les exploitations,
    - Les impacts d'une innovation peuvent varier considérablement d'une exploitation à l'autre, et une innovation peut être très pertinente dans un type d'exploitation et complètement inadaptée dans un autre, révélant ainsi l'existence d'interactions complexes entre innovation et type de ferme.

- De la même manière, au sein d'une exploitation, une innovation peut être performante alors qu'une autre ne l'est pas. Il est donc important de toujours s'efforcer de définir très en amont dans le processus de conception une large gamme d'innovations comme nous l'avons fait pour les cultures associées ou les rotations. C'est en proposant un « panier » d'innovation que chaque agriculteur pourra trouver l'innovation qui lui convient. Il découle de ce résultat que c'est en proposant une large palette d'innovations que l'on pourra améliorer la durabilité globale à l'échelle du territoire.

- Il est important de considérer une large gamme de critères dans l'évaluation *ex ante* d'une innovation. Quelques exemples tirés de notre étude en attestent :
    - o Une innovation peut être performante d'un point de vue environnemental et agronomique et non rentable pour l'agriculteur (exemple : cultures associée avec *Canavalia ensiformis*),
    - o Un système innovant peut être moins productif que le système actuel mais plus rentable (exemple : système Bio avec nouvelle variété), sous certaines conditions de marché.

- Enfin, il est important de prendre en compte les processus d'adoption des innovations dans les programmes de conception et évaluation de systèmes innovants car :
    - o une innovation peut être performantes sur de nombreux critères mais aura une faible chance d'adoption (exemple faible taux d'adoption de l'innovation système Bio)
    - o l'adoption de l'innovation est un processus dynamique, ce qui amène à évaluer les innovations à différents pas de temps, et de manière dynamique sur les différentes parcelles de l'exploitation.

Finalement cette étude confirme que les innovations sont potentiellement porteuses d'un certain nombre d'ambivalences qui rend leur évaluation complexe, renforçant ainsi l'intérêt de conduire des recherches sur les méthodes d'évaluation *ex ante* de systèmes innovants.

6.2.3. Généricité de la méthode

Dans cette section nous avons essayé de voir si la méthode est potentiellement transposable à d'autres contextes. A cette fin, nous avons essayé de raisonner la transposabilité de la méthode à deux contextes très différents de la banane aux Antilles que nous avons choisis pour être très contrastés : les systèmes de culture de blé en France, et les systèmes de culture d'igname au Bénin. En ce qui concerne l'élaboration de la typologie et le prototypage, il semble que la méthode que nous proposons pour bâtir la typologie soit aisément transposable aux deux exemples, car les concepts et méthodes qu'elle utilise sont génériques. En revanche, la phase de prototypage s'appuie sur un panel d'experts et un capital de connaissances agronomiques qui n'existent pas forcément pour les systèmes de cultures d'ignames au Bénin. Néanmoins une analyse bibliographique sur les bases de données internationales devrait permettre de trouver quelques pistes d'innovations, que l'on pourrait aisément adapter au cas de l'igname au Bénin. En ce qui concerne l'étape 2, il s'agit de disposer d'un modèle de culture capable de simuler la culture considérée, et les principaux processus en cause dans les problèmes que l'on résoudre (ravageurs, nutrition minérale, sensibilité aux conditions climatiques, etc.). De nombreux modèles existent pour simuler la culture de blé (APSIM, STICS, CERES, etc.). En ce qui concerne l'igname, bien que certainement le nombre de modèles existants soit faible, des modèles comme EPIC ou CROPsyst semblent suffisamment génériques pour pouvoir être paramétrés à de telles cultures, d'autant plus que ces modèles permettent de simuler des plantes proches comme la pomme de terre. L'approche de modélisation proposée en étape 3 semble facilement applicable dans les deux situations, car les méthodes de représentations des itinéraires techniques et du parcellaire de l'exploitation que nous avons proposées sont génériques. En ce qui concerne l'étape 4, l'approche de modélisation économétrique peut aussi être utilisée dans n'importe quelle situation, car elle l'a déjà été dans de très nombreux contextes.

Ainsi bien qu'un certain capital d'outils et de connaissances sur les innovations soit toujours un plus pour l'efficacité et la rapidité de la démarche, on pourrait dire en première approche que la méthode en elle-même semble tout à fait transposable à d'autres contextes, moyennant évidemment une adaptation des variables au contexte local (variables de la typologie, sorties du modèle que l'on veut étudier, déterminants supposés de l'innovation, etc.).

6.2.4. Pistes d'amélioration de la méthode

Pour conclure cette partie nous proposons deux pistes d'amélioration de la méthode :

- Rendre l'utilisation des modèles beaucoup plus simple et conviviale afin de simuler les impacts des innovations directement chez l'agriculteur. La première partie de l'enquête viserait à collecter les paramètres nécessaires aux simulations avec le modèle, et la deuxième pourrait alors se concentrer sur les conditions d'adoption des innovations en fonction des résultats du modèle, ce qui permettrait d'interagir directement avec l'agriculteur sur les sorties du modèle et de tester d'avantage de scenarii. Cette deuxième phase pourrait d'ailleurs s'inspirer des protocoles construits en économie expérimentale, qui introduirait par exemple automatiquement une variabilité plus ou moins artificielle dans les performances des innovations et permettrait de mieux étudier jusqu'à quel seuil de performances les agriculteurs sont prêts à adopter une innovation. Cela permettrait aussi de fournir à l'agriculteur des simulations encore plus proches de ses conditions réelles, d'explorer une grande gamme d'innovation par agriculteur et d'éviter la simplification typologique que nous avons dû réaliser.

- La deuxième piste d'amélioration est relative à l'intégration de la méthode et des modèles produits dans des plateformes de modélisation portant sur des échelles beaucoup plus grandes et intégrant par exemple des déterminants agissant à des échelles plus globales comme les modèles de marchés et les politiques publiques, comme cela est réalisé dans le projet européen SEAMLESS (van Ittersum et al., 2008). On pourrait ainsi étudier les interactions entre les politiques publiques et l'adoption des innovations technologiques ou entre cette adoption et les effets aggrégatifs sur les prix.

6.3. Propositions d'actions pour l'amélioration de la durabilité des systèmes de cultures bananiers aux Antilles

Le **tableau 1** récapitule par type d'innovation l'ensemble des propositions que nous formulons auprès des différents acteurs de la filière banane aux Antilles : planteurs, agronomes concepteurs, économistes des filières et de l'aide à la décision publique, groupements de planteurs, décideurs.

Ces résultats sont le fruit d'un raisonnement combinant la typologie d'exploitation, les simulations biophysiques, les simulations micro-économiques à l'échelle des exploitations, et les résultats du modèle d'adoption.

Concernant l'usage des nématicides la modélisation biophysique a révélé qu'une suppression de l'usage de ces produits n'affecterait quasiment pas les rendements, permettant ainsi d'économiser des produits coûteux et nocifs pour la santé de l'homme et les biocénoses des écosystèmes naturels et cultivés (diminution de la fertilité biologique des sols par diminution de la diversité de la macrofaune du sol, voir les travaux de Clermont Dauphin et al., 2004).

Objectifs	**Planteurs**	**Agronomes concepteurs**	**Economistes des filières et de l'aide à la décision publique:**	**Groupements de planteurs**	**Décideurs (politiques de soutien)**
Arrêt des traitements nématicides	➢ Nématicides inutiles (types 3 et 4) et inefficaces (types 1, 2, 6)	------	➢ Etudier les déterminants de l'usage des nématicides du point de vue de la psychologie ou de la sociologie comportementale	------	➢ Interdire tous nématicides?
Cultures associées	➢ Quelques recherches complémentaires requises mais *Canavalia ensiformis* très prometteuse pour types extensifs de montagne (5 et dans une moindre mesure 6) ➢ Impatiens peu compétiteur en zone de montagne, il peut être laissé ou moins régulièrement désherbé	➢ Tester *Canavalia ensiformis on farm* ➢ Entretien manuel coûteux: o Les cultures associées doivent aussi rendre un service économique o Trouver des couverts pérennes à faible développement végétatif (moindre encombrement), en particuliers pour la Martinique (présence serpent). ➢ Quel est l'impact des cultures associées sur les autres ravageurs de la banane (charançon, thrips, etc.)? ➢ Etude de sensibilité aux saisons sèches	➢ Comment organiser la production de semences ? ➢ Quel conseil technique donner?	➢ Comment organiser l'approvisionnement en semences et le conseil technique?	➢ Mettre en place des subventions compensatoires d'au moins 400€/ha/an pour types 1, 2, 4, et 5 et de 800€/ha/an pour types 3 et 4, pour *Canavalia ensiformis*. ➢ Autres cultures associées nécessiteraient un soutien dépassant le plafond de 900€/ha/an ➢ Nécessite recherches complémentaires
Rotations et jachères améliorées	➢ Indispensables pour tous les types qui n'ont pas encore adopté mais doit être réalisé dans de bonnes conditions (mode de destruction parcelle, entretien et durée jachère)	➢ Trouver une solution pour le travail du sol en zone non mécanisable (au niveau de la plante de couverture, ou petite mécanisation adaptée) ➢ Trouver des plantes fortement némato-régulatrices pour réduire la durée de la rotation à quelques mois ➢ Trouver des cultures de vente à cycle très court, qui pourrait être enchaînées, némato-régulatrices, et compatible avec la présence de chlordécone dans les sols, ou des cultures énergétiques ? ➢ Crotalaires non adaptés à la Martinique (Serpent)	➢ Parmi les cultures de rotations possibles, quels sont celles dont la filière est la suffisamment structurée et le marché ouvert et accessible aux producteurs Antillais (export ou marché local ?)	➢ Promouvoir l'adoption de la jachère et des vitro-plants par une politique de communication spécifique au près des planteurs	➢ Mettre en place des mesures de subventions à la conversion du type micro-crédits de 5000€ lors de la mise en jachère, remboursable en 3 ans, à partir de 2 ans après l'adoption. ➢ Nécessite recherches complémentaires
Nouvelles variétés de banane	➢ Innovation prometteuse mais nécessite recherches complémentaires	➢ Si le prix de vente est le même que celui de la banane conventionnelle, il faudrait alors des variétés plus productives ou des bananiers moins hauts	➢ Evaluer *ex ante* les conditions de réussite et d'appropriation de cette innovation à l'échelle de la filière (transport, mûrisseur, GMS, consommateur) ➢ Combien le consommateur européen est il prêt à payer pour une banane avec des caractéristiques différentes des Antilles (goût nouveau, pratiques durables, petit format de banane)?	➢ Dans l'état actuel cette banane doit être vendue au moins 0.78€/kg (types 1, 2, 5, 6) et 0.92€/kg (type 3 et 4) pour être plus rentable que la banane actuelle	➢ Innovation prometteuse mais nécessite recherches complémentaires
Systèmes à cycles intégrés	➢ Innovation prometteuse mais nécessite recherches complémentaires	➢ Explorer des modalités d'innovation type culture de rotation pérenne, semis sous couvert végétal vivant, et plante de couverture devenant culture associée, si possible fixatrice (type trèfle ?)	------	➢ Innovation prometteuse mais nécessite recherches complémentaires	➢ Cf. culture associée + rotations et bonus environnemental supplémentaire?
Banane biologique	➢ Innovation prometteuse mais nécessite recherches complémentaires	➢ Evaluer le modèle SIMBA sur ces systèmes très innovants par confrontation avec données expérimentales	➢ Combien le consommateur européen est il prêt à payer pour une banane BIO des Antilles? (modèles économétriques hédoniques?)	➢ Quelles modalités de mise en place : intrants, label, conseil ? ➢ Prix doit être > 0.78€/kg (types 1, 2, 5, 6) et 1.13€/kg (type 3 et 4)	➢ Innovation prometteuse mais nécessite recherches complémentaires

Tableau 1 : Propositions pour les différents acteurs de la filière à l'issu du travail. Nota : ne pas hésiter à consulter l'UR APC de l'INRA avant toute prise de décision à partir de ce tableau.

En effet les types 1, 2 et 6 qui pratiquent la monoculture, utilisent trop peu de traitements nématicides pour que ceux-ci soient efficaces. Les types 3 et 4 qui pratiquent des rotations assainissantes continuent d'utiliser ces produits alors qu'ils ne semblent pas nécessaires. Cela pourrait être expliqué par plusieurs hypothèses : les produits actuels autorisés étant mixtes (nématicide et insecticide à la fois), leur usage correspond en fait à une volonté de contrôler uniquement les insectes, et il faudrait alors utiliser des produits insecticides seulement. Il pourrait aussi être intéressant d'étudier les déterminants de cet usage à travers une analyse sociologique ou de psychologie comportementale.

En ce qui concerne les cultures associées, seule *Canavalia ensiformis* s'est révélée rentable et pour seulement un type d'exploitation (type 5). Cela s'explique par le fait Il faudrait désormais tester cette innovation dans le contexte de ce type d'exploitation. Pour les autres types cette culture associée n'est pas rentable car le surcoût en travail engendré par l'entretien de la plante de couverture n'est pas compensé par le gain de rendement. Néanmoins il pourrait être pertinent de favoriser l'adoption de cette innovation et de la promouvoir en compensant les pertes dues à l'adoption. Celles-ci sont en effet compatibles avec les plafonds légaux de subventions dans le cadre de MAE (900€/ha/an), et l'adoption de cette innovation pourrait permettre de réduire les usages d'herbicides qui sont présents dans toutes les exploitations.
Au-delà de ce constat, des recherches complémentaires doivent cependant être entreprises sur les plantes de services afin d'en optimiser la conduite et parfaire l'évaluation *ex ante* à plusieurs niveaux qui n'ont pas été abordés ici. Dans ce sens il faudrait peut être réaliser un nouveau criblage de plantes de services en intégrant les contraintes et préférences des agriculteurs. Ainsi le faible taux d'adoption de cette innovation en Martinique, qui pourrait être expliqué par la présence du dangereux serpent *Bothrops lanceolatu* sur cet île, pourrait amener à cibler des plantes ou des configurations spatiales de cultures intercalaires qui sécuriserait le passage de l'opérateur au champ. De la même manière il faudrait s'efforcer d'une manière générale de trouver des plantes de services rendant aussi un service économique car la substitution des herbicides (produits peu chers) par du travail (cher) n'est pas rentable toute chose étant égale par ailleurs.
Par ailleurs il faudrait également évaluer quel serait l'impact des cultures associées sur la présence d'autres ravageurs comme le charançon, et les bioagresseurs qui pourraient amoindrir la qualité visuelle de la banane (thrips, araignée rouge, virus de la rouille argentée, etc.).

La pratique des rotations semble incontournable car elle permettrait d'augmenter considérablement les faibles rendements en banane de certaines exploitations. Cependant leur adoption peut être problématique pour les petites exploitations (types 1 et 6 surtout, et dans une moindre mesure types 2 et 5) car elle entraînerait une période transitoire de 2 à 4 ans où le revenu des planteurs baisserait considérablement, alors que ces planteurs n'ont pas accès au crédit et ont une trésorerie faible. Ces contraintes devraient néanmoins pouvoir être levées avec des mesures du type de celles présentées dans le tableau 1.
Diverses recherches sur les rotations doivent encore être entreprises car très peu d'options ont été explorées : on pourrait par exemple imaginer des rotations entre banane et enchaînement de plusieurs cycles courts de cultures maraîchères qui peuvent être vendues sur le marché local. Cela pourrait par exemple être des solanacées (tomate, aubergine), dont les organes commercialisées sont indemnes de chlordécone (Jannoyer et Cabidoche, 2008), contrairement aux cucurbitacées qui pourraient concentrer de manière significative cette molécule dans des teneurs proches des limites règlementaires de 20µg/kg. Il faudrait néanmoins étudier leur effet sur les populations de nématodes afin de voir si elles seraient efficaces du point de vue de l'assainissement de la parcelle.

En ce qui concerne les nouvelles variétés de banane, celles-ci souffrent d'une productivité moindre. Elle doivent donc être vendues à un prix de vente plus élevé (0.92€/kg pour être rentable pour tous les types d'exploitations), et il faudrait étudier quel prix les consommateurs européens seraient prêts à payer pour cette banane aux caractéristiques très innovantes : goût nouveau, petit format, issue d'une production à très bas niveau de pesticides. Cela pourrait être fait avec des modèles économétriques hédoniques (Rosen, 1974 ; Langyintuo et al., 2005). Il faudrait également évaluer *ex ante* comment se comporterait cette innovation dans le circuit de commercialisation, depuis les bananeraies des Antilles jusqu'aux GMS de métropole.

En ce qui concerne la banane biologique, les résultats obtenus sont très prometteurs sur le plan agronomique et économique. Il faudrait cependant tester la validité de plusieurs paramètres de notre évaluation *ex ante* : évaluer à quel prix de vente cette banane pourrait effectivement être vendue (si ce prix est le double du prix de la banane conventionnelle, alors cette innovation est plus rentable que les systèmes actuels pour tous les types), et tester en exploitation agricole la productivité de cette innovation, en comparaison du rendement simulé avec le modèle SIMBA.

Ceci dit, la probabilité d'adoption de cette innovation est faible (35%). Cela peut être expliqué par l'absence de croyance en l'ouverture de marchés pour des bananes éco-labellisés, l'incertitude pesant sur la filière banane et ses politiques de soutien, les attitudes d'aversion au risque et à l'incertitude, qui sont toutes à mettre en relation avec d'une part le contexte de crise toujours prégnant et le caractère très innovant de ce système qui comporte pas moins de 4 innovations individuelles majeures (pratique d'une jachère améliorée, culture associée, fertilisation organique, arrêt de tout pesticide).

6.4. Conclusion générale

Dans le cadre des travaux présentés ici, une tentative d'articulation d'outils de nature biophysique et socio-économiques a été proposée et testée, afin de conduire un prototypage et une évaluation *ex ante* de systèmes candidats à l'innovation, de manière multi-critère, à l'échelle de l'exploitation agricole, et prenant en compte les conditions d'adoption et la diversité régionale des exploitations.

A travers la prise en compte des contraintes réelles et des préférences hétérogènes des agriculteurs, cette approche a permis d'évaluer quels seraient les impacts et les conditions d'adoption de nouveaux systèmes de culture, plus durables. La sortie du travail est un ensemble de propositions d'actions et d'outils à destination des agronomes concepteurs, des économistes de l'innovation, et des acteurs de la filière afin d'orienter ou réorienter la conception et l'évaluation des innovations, afin de maximiser leurs chances de réussite.

Pour conclure cette thèse, nous soulignerons que la modélisation *ex ante* de l'adoption de l'innovation par les agriculteurs nous semble être un domaine de recherche très porteur. En effet, à travers la prise en compte des multiples paramètres qui rentrent dans la décision d'un agriculteur d'adopter ou non une innovation, c'est un grand nombre de concepts et d'outils issus des disciplines agronomiques et économiques et sociales qui doivent être mobilisés. Cette convergence des concepts et outils nous semble fertile pour contribuer à renouveler dans chaque discipline les questions de recherche autour de la conception de systèmes agricoles innovants, mais également pour favoriser l'émergence de résultats de recherche et d'outils plus à même de faire converger les attentes des agriculteurs, des filières et de la société dans son ensemble.

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Annexe : photos d'éléments des systèmes innovants

A. Cultures et jachères en rotation avec la banane

Culture d'ananas

Jachère de Crotalaria juncea

Jachère de Brachiaria decumbens

Nota : Expérimentation chez un planteur. Martinique.

Jachère contrôlée chimiquement

Nota : Innovation pratiquée chez un planteur. La jachère est à gauche, à droite se trouve une bananeraie et le hangar de la station de conditionnement. Guadeloupe.

B. Cultures associées aux bananiers

Canavalia ensiformis

Nota : Expérimentation sur le domaine de Duclos (INRA)

Bananeraie avec interculture d'Impatiens sp.

Nota : Photo prise dans une bananeraie d'altitude en Guadeloupe

C. Nouvelle variété hybride de banane :

Variété hybride de banane

Nota : Expérimentation CIRAD

http://snoopy.bondy.ird.fr/ezpublish/index.php/PRAM/content/download/43893/139572/version/2/file/Innovation+vari%C3%A9tale+Banane.pdf

D. Systèmes intégrés

Système sans intrants chimiques

Nota : interrang couvert avec *Canavalia ensiformis*, fertilisation organique, précédent jachère. Expérimentation chez un planteur. Guadeloupe

Bananiers plantés sur un couvert végétal vivant de Brachiaria Decumbens

Nota : Expérimentation chez un planteur. Martinique.

EVALUATION EX ANTE DE SYSTEMES DE CULTURE INNOVANTS PAR MODELISATION AGRONOMIQUE ET ECONOMIQUE : DE LA CONCEPTION A L'ADOPTION

Cas des systèmes de cultures bananiers de Guadeloupe

Jean-Marc Blazy, 2008

Face à la multiplication et la complexité croissante des objectifs assignées à l'agriculture, les méthodologies de conception et d'évaluation *ex ante* de systèmes de culture innovants font l'objet d'un effort de recherche très soutenu. Cependant malgré le foisonnement de recherches et de productions d'outils disciplinaires, peu de recherches d'interface ont été entreprises, ce qui limite les possibilités d'évaluations *ex ante* globales des systèmes innovants, de la conception à l'adoption par les agriculteurs. L'objectif de cette thèse est de contribuer à l'avancée de ces travaux, en proposant une méthode transdisciplinaire d'évaluation *ex ante* de systèmes de culture innovants basée sur la combinaison d'outils de modélisation issus de l'agronomie et de l'économie. A partir d'une analyse de la littérature actuelle et de ses forces et faiblesses, nous construisons une méthode originale qui se décompose en 4 étapes : i) modélisation de la diversité des exploitations et prototypage de systèmes innovants plus durables, ii) utilisation d'un modèle de culture pour simuler le fonctionnement biophysique des innovations dans les types d'exploitations, iii) évaluation des impacts de l'adoption sur le fonctionnement et les performances des types d'exploitation à l'aide d'un modèle bio-économique d'exploitation, iv) modélisation *ex ante* de l'adoption par les planteurs à l'aide d'un modèle économétrique.

La méthode est ensuite appliquée à la conception et à l'évaluation *ex ante* de prototypes de systèmes de cultures bananiers aux Antilles françaises, qui traversent actuellement une crise socio-économique et environnementale sévère. L'application de la première étape de la méthode a permis d'identifier 6 types d'exploitations très contrastés avec des problèmes de durabilité se déclinant différemment et de mettre au point 16 prototypes de systèmes innovants impliquant plante de couverture cultivées en association ou en rotation, nouvelles variétés de bananiers, et réduction de l'usage des intrants chimiques. La deuxième étape a montré que les performances agronomiques des prototypes peuvent varier considérablement d'un type d'exploitation à un autre, et que certains systèmes semblent très prometteurs sur le plan agronomique et environnemental. Cependant les modélisations réalisées en étape 3 et 4 montrent que d'une part, des innovations performantes à la parcelle peuvent poser des problèmes de trésorerie et de charge de travail à l'échelle de l'exploitation, et que d'autre part certaines innovations très prometteuses ont pourtant un taux d'adoption faible. Les résultats du modèle économétrique et des simulations réalisées en étapes 2 et 3 permettent alors de définir un ensemble de propositions d'action à destinations des acteurs de l'innovation et du développement en vue de maximiser les chances d'adoption de systèmes plus durables.

Le dernier chapitre de cette thèse revient sur les forces et les faiblesses de la méthode et souligne sa généricité potentielle qui devrait donc permettre d'étendre son application à d'autres contextes afin d'assurer une meilleure adéquation entre les innovations produites par la recherche agronomique et les attentes des agriculteurs et de la société.

Mots-clés : innovation, évaluation *ex ante*, adoption, modélisation, approche transdisciplinaire.