Évaluation régionalisée de l'émission et de la séquestration du carbone dans les sols tropicaux de Guadeloupe (TROPEMIS)

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Evaluation régionalisée de l'EMISsion et de la séquestration de carbone dans les sols TROPicaux de Guadeloupe (TROPEMIS)

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Rapport Final

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SOMMAIRE

Abréviations : BD, base de données, CC, changement climatique ; GES ; gaz à effet serre ; SdC, système de culture.

I- Contexte et rappel des objectifs

L'intensification de l'agriculture est la responsable principale de l'augmentation des émissions de GES et de la réduction des stocks carbonés des sols dans les tropiques. L'information disponible indique que la situation aux Antilles françaises présenterait cette même tendance, avec des diminutions des stocks carbonés de l'ordre de 5-10% depuis les années '90 pour certains SdC. Cette réduction pourrait s'accentuer dans les prochaines années à cause du CC, notamment dans les SdC voués à la production de biomasse en raison de la diminution des entrées de C au sol, ce qui affecterait l'efficacité énergétique globale de la filière.

Dans le contexte à information restreinte qui caractérise les Antilles, l'appropriation et la fiabilisation des mesures et des pratiques agroenvironnementales destinées à atténuer le CC, nécessitent préalablement une meilleure évaluation des effets des SdC et de la diversité des milieux pédoclimatiques sur les émissions de CO_2 et sur la séquestration de C dans les sols. Les objectifs visés par TropEmis découlent directement de ce constat et répondent aux attentes de l'Axe 1 de REACCTIF. **L'objectif scientifique était d'analyser et modéliser les interactions entre les émissions/séquestration de C et la diversité des milieux et des SdC en Guadeloupe. Du point de vue finalisé, il s'agissait d'améliorer l'outil d'évaluation MorGwanik, destiné à la profession agricole et les décideurs, dont le but est d'estimer les flux et le stock carbonés des sols, pour donner ainsi des pistes sur les voies de préservation de la ressource sol et d'atténuation du CC.** Cette retombée attendue du projet a constitué l'un de ses aspects novateurs, notamment en milieu tropical. D'autres GES n'ont pas été traités dans ce projet du fait que les propriétés pédoclimatiques et la gestion des SdC rendent leur flux peu importants dans les sols agricoles antillais.

TropEmis a fait appel aux connaissances que l'INRA en Guadeloupe avait acquises sur le fonctionnement carboné des sols, y compris l'impact du CC, et à l'expérience que Carib Agro avait accumulé sur les SdC caribéens et les propriétés des sols antillais, pour les articuler autour d'un outil d'évaluation simple et appropriable. Cette information a été revisitée et complétée par des enquêtes agronomiques concernant la gestion et le statut organique actuel des sols, en tenant compte de la diversité des milieux et des SdC (Tâche 2). Des expérimentations de laboratoire ont permis de cerner et de modéliser l'effet de ces variables sur les émissions de CO_2 et le stock carboné des sols (Tâche 3). L'ensemble de l'information ainsi obtenue a été utilisée pour améliorer la BD de MorGwanik et adapter cet outil afin d'élargir la gamme des problématiques abordées (p.ex. lutte contre le CC) (Tâche 4). Afin d'assurer, d'une part, la pertinence de la sélection des sites à enquêter et, d'autre part, une dissémination efficace des résultats attendus, un réseau a été co-construit avec les acteurs locaux du développement agricole (Tâche 5).

Une des principales stratégies de valorisation des résultats, au-delà des publications de nature scientifique, a été sa mise à disposition auprès d'un vaste public, constitué de professionnels de l'agriculture, d'enseignants et de décideurs. Cette dissémination a été assurée via des livrables opérationnels (MorGwanik, carte des stocks carbonés) et des opérations de communication telles que des séminaires de restitution et des journées techniques.

II- Structuration et participants au projet

La Figure 1 présente les cinq tâches autour desquelles le projet s'est structuré, et les fonctions principales de chaque tâche. La stratégie et la gestion du projet ont été de la responsabilité de la tâche 1 (T1 : **Jorge Sierra, DR INRA**), y compris la gestion des produits finaux. Les tâches 2 (T2 : **François Causeret, IE INRA** ; **Dominique David, Ing. Agr. Carib Agro** ; **Aurore Cavalier, IE CDD INRA**) et 3 (T3 : **Lucienne Desfontaines, IE INRA** ; **Jorge Sierra** ; **Franck Solvar, TR INRA** ; **Jocelyne Leinster, TR INRA**) ont concentré les activités associées à la production et le traitement des données et de l'information (terrain et laboratoire, respectivement). Les résultats/produits attendus de ces tâches sont la carte simplifiée de stocks de carbone (T2), et la quantification des relations émission/séquestration vs. SdC/milieu (T3). La tâche 4 (T4 : **Mirza Publicol, IE INRA**) a concerné l'intégration de cette information dans l'outil informatique MorGwanik, ce que correspond au produit final de cette tâche. Finalement, la tâche 5 (T5 : **Jean-Louis Diman, IE INRA** ; **Dominique David**) a été dédiée au développement des échanges avec la profession agricole et à la définition d'une stratégie pour le transfert et la vulgarisation des résultats. Le produit final est la formalisation d'un réseau de collaboration avec la profession agricole. Bien que T2 et T5 ont été extrêmement liées, notamment en début du projet, en raison de sa valeur stratégique sa liaison a été faite avec la participation du coordinateur du projet.

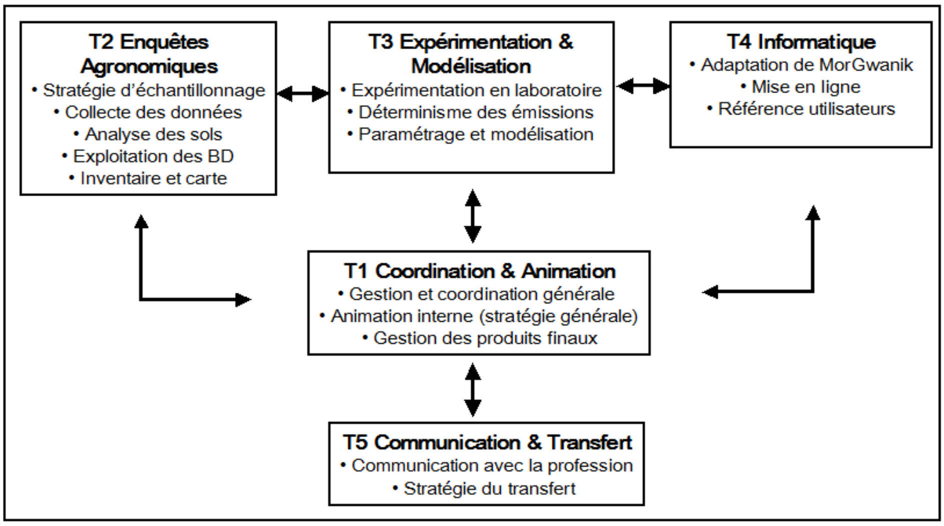


Figure 1 : Organigramme technique.

III- Démarche de l'étude

La première étape de cette étude a concerné l'évaluation de la BD de Carib Agro comportant environ 5000 analyses de sol depuis 1998 ; p.ex. nom et coordonnées de l'exploitation et de l'exploitant, coordonnées géographiques, commune et section, type du sol, culture présente au moment du prélèvement du sol, teneurs en carbone, azote, phosphore et cations, capacité d'échange cationique, pH (Figure 2). Cette évaluation a été réalisée avec un programme mis au point par M. Publicol (T4) et nous a permis d'identifier six populations des parcelles au sein de la BD :

Population 1- parcelles avec plus d'une analyse diachronique : *au moins une analyse a été réalisée dans le passé (< année 2010), *au moins une analyse a été réalisée dans le présent (> 2010), *la différence entre l'analyse la plus récente et la plus ancienne est d'au moins 5 années.

Population 2- idem 1- mais la différence entre les deux analyses est de <5 années.

Population 3- parcelles avec une seule analyse réalisée dans le présent.

Population 4- idem 1- mais toutes les analyses ont été réalisées dans le passé.

Population 5- idem 2 mais toutes les analyses ont été réalisées dans le passé.

Population 6- idem 3 mais l'analyse a été réalisée dans le passé.

Les populations 1, 2 et 3 ont été sélectionnées pour alimenter la carte actuelle de stock de carbone en Guadeloupe (703 parcelles). Les populations 1, 2, 4 et 5 ont été sélectionnées pour calibrer (159 parcelles) et tester (94 parcelles) le modèle MorGwanik. L'information de la BD a été complétée par des **enquêtes agronomiques et des prélèvements des sols** chez l'agriculteur (382 agriculteurs). **La sélection des agriculteurs à enquêter a été réalisée en collaboration avec la profession agricole**.

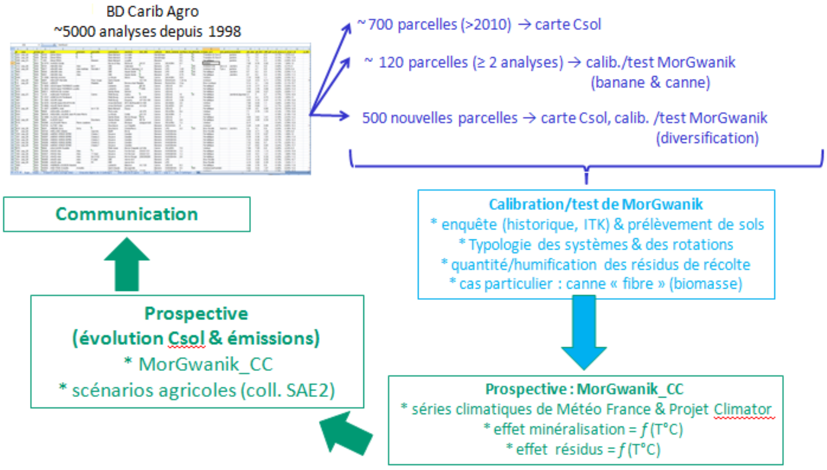


Figure 2 : Démarche de l'étude.

La carte de stock carboné est ainsi construite avec **1085 parcelles** (703 de la BD et 382 nouvelles parcelles). La calibration et le test du modèle a été réalisée avec :

37 parcelles cultivées en banane sur andosol (zone 3),

33 parcelles cultivées en banane et en canne sur ferralsol (zone 2),

11 parcelles cultivées en banane sur nitisol (zone 4),

26 parcelles cultivées en canne sur vertisol (zone 1) ,

(total : 107 parcelles pour les monocultures d'exportation),

15 parcelles en maraîchage sur andosol (zone 3),

24 parcelles en maraîchage sur vertisol (zone 1),

2 parcelles en maraîchage sur ferralsol (zone 2),

2 parcelles en maraîchage sur nitisol (zone 4),

49 parcelles en ananas sur ferralsol (zone 2)

20 parcelles en melon sur vertisol (zone 1),

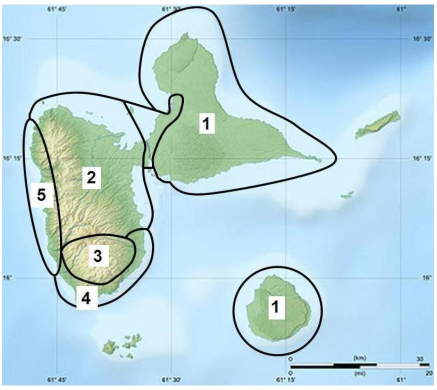
8 parcelles en igname sur ferralsol (zone 2),

16 parcelles en igname sur vertisol (zone 1),

10 parcelles en verger (agrumes) sur sol vertique (zone 5).

(total : 146 parcelles pour les cultures de diversification).

Les zones correspondent aux régions pédoclimatiques présentées dans la Figure 3.



Région 1 : Vertisols ; Climat subhumide ; Spéculations : canne, élevage, diversification.

Région 2 : Ferralsols ; Climat humide ; Spéculations : canne, diversification, élevage.

Région 3 : Andosols ; Climat hyper-humide ; Spéculations : banane, diversification (canne à fibres future).

Région 4 : Nitisols ; Climat humide ; Spéculations : banane, diversification (canne à fibres future).

Région 5 : Sols vertiques; Climat subhumide; Spéculations : verger, diversification, élevage.

Figure 3 : Les régions pédoclimatiques de la Guadeloupe

La calibration et le test du modèle a été donc réalisée avec :

* l’information du suivi diachronique du stock carboné issue de la BD et des prélèvements effectués dans le cadre du projet : 253 parcelles en total (Tâche 2);

* l’information issue des enquêtes : rotation, rendements, gestion de résidus de récolte et des amendements organiques (Tâche 2) ;

* la relation rendements vs. résidus de culture issue d’un travail de calibration de terrain réalisé dans le cadre du projet (Tâche 2) (Figure 2) ;

* de l’information sur l’humification des amendements organiques et des résidus de culture issue des expérimentations en laboratoire réalisées dans le cadre du projet (Tâche 3) (Figure 2).

Nous avons calibré deux paramètres (voir détail en Annexe 5) : le coefficient de minéralisation de la matière organique du sol (i.e. différente pour chaque région agro-écologique, k_{AER}[1]) et le coefficient de culture (i.e. différente pour chaque SdC, k_{CROP}). **Le reste des paramètres a été fixé et est issu des expérimentations indépendantes du suivi de terrain et de laboratoire**. **Afin de la rendre plus robuste en termes statistiques, la calibration et le test ont été effectués en plusieurs étapes** :

1) calibration et test du système banane/andosol : estimation de k_{AER} de la région 3 et de k_{CROP} de la banane ;

2) calibration et test du système canne/vertisol : estimation de k_{AER} de la région 1 et de k_{CROP} de la canne ;

3) calibration et test des systèmes banane et canne/ferralsol : estimation de k_{AER} de la région 2 (en fixant k_{CROP} de la banane et k_{CROP} de la canne) ;

4) calibration du système banane/nitisol : estimation de k_{AER} de la région 4 (en fixant k_{CROP} de la banane) ;

5) calibration du système verger/vertique : estimation de k_{AER} de la région 5 et k_{CROP} du verger ;

6) calibration et test de chaque SdC de diversification (maraîchage, melon, ananas, igname) : estimation du k_{CROP} de chaque SdC (en fixant les k_{AER} des régions concernées).

Pour le cas particulier du maraîchage, et compte tenu du manque d’information sur ce type de SdC en Guadeloupe, nous avons réalisé une typologie des parcelles à partir des résultats des enquêtes et des mesures du stock carboné dans les sols. Cela nous a permis de mettre en évidence l’impact des pratiques culturales sur la fertilité organique, dans un SdC qui peut promouvoir sa dégradation et une émission importante de CO_2 à cause de son intensification.

IV- **Livrables réalisés et résultats obtenus**

Les livrables réalisés sont présentés en ordre chronologique d'élaboration afin de donner un aperçu du déroulement du projet. Les résultats obtenus sont détaillés dans les livrables.

1) Dépliant TropEmis (voir Annexe 1)

Ce dépliant a été élaboré par les participants de T5 et T2 afin d'informer les agriculteurs sélectionnés sur les objectifs du projet avant la réalisation des enquêtes. Il a été distribué avec la collaboration de la profession agricole (SICAs, associations, Chambre d'Agriculture).

2) Carte de carbone organique (voir Annexe 2)

Comme il a été mentionné plus haut, cette carte est issue des analyses réalisées dans le cadre du projet (i.e. 2013-2014, 382 parcelles) et des analyses contenus dans la BD de Carib Agro et réalisées entre 2010 et 2012 (703 parcelles). Nous rappelons que l'objectif n'était pas d'élaborer une carte détaillée des teneurs en carbone organique, mais de réaliser un outil de vulgarisation destiné à visualiser aisément la situation actuelle des sols de Guadeloupe, afin de sensibiliser les décideurs et la profession agricole à la problématique du changement climatique. Dans ce sens, la présentation de

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[1] AER : agro-ecological region

la carte dans les réunions et les documents de restitution était un préalable à la discussion sur les impacts du changement climatique et sur les adaptations possibles (voir Annexes 3 et 4).

3) Diaporama de restitution finale (voir Annexe 3)

Ce diaporama a été présenté lors de la restitution finale du projet le 19 juin 2015, en présence des décideurs, des bailleurs de fonds et de la profession agricole. Il contient les résultats essentiels du projet : diagnostic de la situation actuelle de la fertilité organique des sols, impact du changement climatique sur les émissions de carbone et les adaptations possibles. Il a été distribué aux participants de la restitution et à l'ensemble des partenaires du projet.

4) Synthèse des résultats (voir Annexe 4)

Cette synthèse a été réalisée à la demande du Conseil Régional de la Guadeloupe, l'un des bailleurs de TropEmis, pour être distribuée aux services régionaux concernés par l'agriculture, l'environnement et le développement endogène.

5) Article scientifique "Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe", publié en *Agriculture, Ecosystems and Environment* 213 (2015) 252–264 (voir Annexe 5)

Il s'agit du premier article scientifique issu du projet TropEmis. Il présente la démarche théorique et expérimentale mise en œuvre pour calibrer et tester le modèle MorGwanik, et les résultats obtenus sur l'évolution des teneurs en carbone organique pour la période 1998-2014 pour les différentes régions pédoclimatiques et systèmes de culture de Guadeloupe.

6) Mise en ligne de MorGwanik

http://toolsforagroecology.antilles.inra.fr/morgwanik/index.php/morgwanik/

Nous avons modifié le logiciel original de 2011 pour introduire les paramètres obtenus dans le cadre de TropEmis, y compris ceux liés à l'impact du changement climatique. Il s'agit d'un outil destiné à la profession agricole et les décideurs et est en accès libre sur le site de l'INRA Antilles-Guyane. Il est actuellement en évaluation par un groupe de partenaires du projet afin de réaliser un feedback sur les améliorations à apporter au logiciel pour le rendre appropriable pour le plus grand nombre.

Dans le cadre de la Fête de la Science 2015, organisée en interne par la mission Science et Société de l'INRA Antilles-Guyane, MorGwanik sera utilisé pour sensibiliser des élèves de 3ème à 1ère aux effets du changement climatique sur l'agriculture en Guadeloupe.

7) Diaporama de présentation au programme *Prospective 2040 Guadeloupe* (voir Annexe 6)

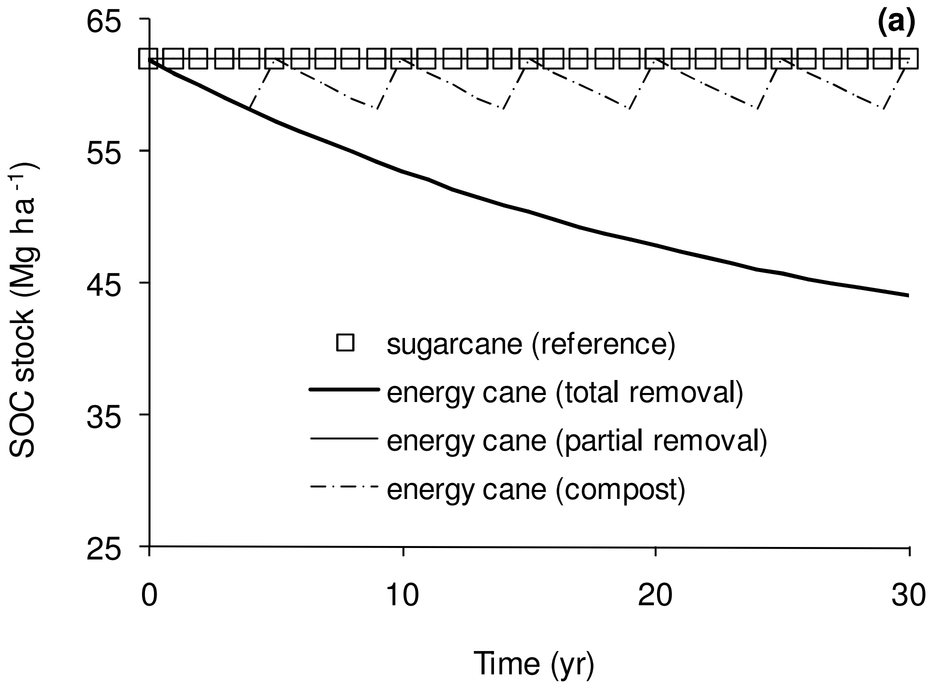
Ce programme, animé par la Chambre d'Agriculture de Guadeloupe et financé par le Feader, a pour objectif l'élaboration des propositions sur l'évolution de l'agriculture en Guadeloupe en relation aux changements globaux. Nous avons été invités à la réunion du Comité de Pilotage du programme le 21 septembre 2015 afin de discuter autour du sujet Changement Climatique & Agriculture en Guadeloupe. Notre présentation a concerné les résultats des projets Climator (ANR) et TropEmis. La même présentation sera réalisée dans le cadre de la conférence sur l'Agriculture et le Changement Climatique organisée par la DAAF, le 25 novembre 2015.

V- Livrables à réaliser

1) Article scientifique "Optimisation of biomass and compost management to sustain soil organic matter in energy cane cropping systems in a tropical long-term polluted soil" par J. Sierra, J.L. Chopart, L. Guindé et J.M. Blazy. A soumettre à *BioEnergy Research*.

Ce papier est actuellement en phase de révision par les co-auteurs et sera soumis mi octobre. Il s'agit d'une analyse du système "canne énergie" proposé par la Région Guadeloupe pour conserver sous agriculture les terres polluées par le pesticide chlordecone. Nous avons couplé les modèles MorGwanik et Wisorch, qui décrit la dynamique de la chlordecone dans le sol, afin d'optimiser la gestion de la biomasse produite par la canne pour éviter l'augmentation d'émissions de carbone du sol et le déstockage et lessivage du pesticide. Ce travail a été réalisé en collaboration avec le projet Rebecca (Recherche Biomasse-Energie Canne à Capesterre Belle-Eau) financé par le Feder.

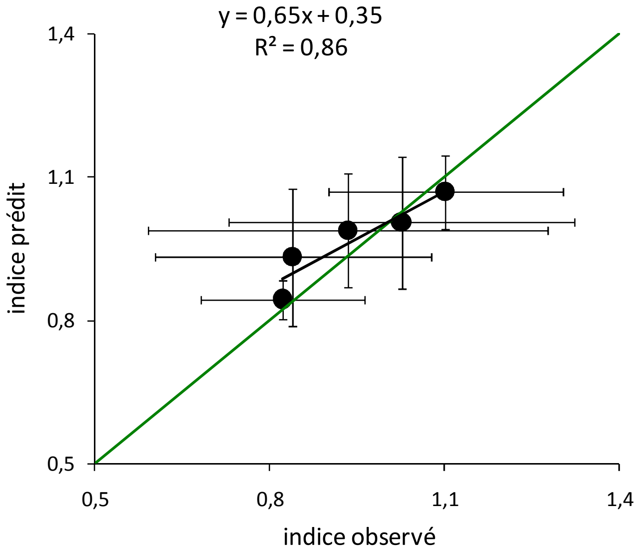
Exemple de résultat obtenu: la figure ci-dessous montre les résultats des simulations réalisées avec MorGwanik pour une monoculture de "canne énergie" dans un sol pollué par la chlordecone. Le système qui restitue une partie (optimisée) de la biomasse produite par la canne (p. ex. partial removal) permet de conserver le niveau de carbone organique dans le sol. Le système avec une récolte totale de la biomasse et une application (optimisée) de compost tous les cinq ans (p. ex. compost) permet de conserver le carbone organique sur l'ensemble de la période analysée. Finalement, le système avec une récolte totale de la biomasse et sans restitution additionnelle de carbone (p. ex. total removal) induit une perte de carbone de l'ordre de 25%; dans ce cas, la perte de la chlordecone stockée dans le sol est de 13%, ce qui peut augmenter le degré de pollution (résultats sur la chlordecone non montrés). L'ensemble des résultats indique qu'une réduction des restitutions carbonées dans un système vouée à la production de biomasse entrainera une augmentation d'émissions de carbone ainsi qu'une pollution accrue de l'écosystème.



2) Article scientifique "Combining a typology and a model of SOM dynamics to assess the impact of farming practices on carbon dioxide emissions from tropical soils".

Il s'agit d'une étude réalisée sur le maraîchage dans le cadre de TropEmis. Ce système est celui qui présente les plus fortes émissions de dioxyde de carbone du sol en Guadeloupe. Nous avons mis en évidence que les variables qui définissent la typologie du système (pédoclimat, type et durée des rotations, utilisation des amendements organiques, taille de l'exploitation) peuvent être incorporés au modèle MorGwanik afin de restituer l'évolution d'émissions de carbone pour chaque type d'agriculteur. Cela ouvre de perspectives intéressantes pour l'identification des mesures d'adaptation au changement climatique ajustées aux caractéristiques spécifiques de chaque groupe. Le papier est en phase de rédaction et sera soumis début 2016.

Exemple de résultat obtenu: la figure ci-dessous montre la relation entre les indices d'émission de carbone du sol observés et prédits avec le modèle MorGwanik. L'indice correspond au quotient entre l'émission moyenne de carbone pour la période 1998-2014 d'une parcelle donnée et la valeur de référence pour cette parcelle. La valeur de référence est celle correspondant à la monoculture qui a précédée le maraîchage (p. ex. canne à sucre dans les régions 1 et 2, banane dans les régions 3 et 4). Un indice >1 implique que le maraîchage a provoqué une augmentation d'émissions de carbone en relation au système précédent. La combinaison de typologie et modélisation mécaniste nous a permis d'identifier les facteurs et les pratiques qui affectent l'émission de carbone, et ainsi proposer des mesures de mitigation adaptées à chaque groupe d'agriculteur. Les cinq groupes identifiés sont: maraîchage spécialisé pluvial de montagne, maraîchage intensif avec jachère, maraichage extensif avec jachère, maraîchage extensif avec diversification et maraîchage intensif spécialisé.



3) Couplage de MorGwanik et Mosaïca[2]

Mosaïca est un modèle élaboré dans l'Unite Astro pour analyser, d'une manière spatialement explicite, les évolutions des systèmes agricoles à l'échelle du territoire. Il permet d'élaborer des scenarii d'évolution de l'agriculture (p. ex. mosaïque des systèmes) en fonction des objectifs divers (optimisation économique, protection de l'environnement, augmentation de la biodiversité cultivée, réduction de la pollution des ressources hydriques, etc.). Notre objectif est de coupler ce modèle à MorGwanik afin d'évaluer la performance de chaque scenario en termes d'émissions de carbone sous l'impact du changement climatique. Actuellement nous travaillons sur l'approche à appliquer afin de définir les rotations de culture sous chaque scenario et pour chaque région pédoclimatique de Guadeloupe.

VI- Conclusions et remerciements

Les objectifs du projet ont été atteints, notamment en ce qui concerne le déterminisme et l'hiérarchisation des facteurs responsables d'émissions de carbone dans les sols agricoles de Guadeloupe (Annexes 4 et 5). Le double principe qui sous entendait le projet, en termes de production de connaissances et de création de supports pour le transfert et la vulgarisation, a guidé nos actions et nous a permis d'élaborer un nombre satisfaisante de livrables scientifiques et de communication. La démarche de sensibilisation aux impacts du changement climatique que nous avons entrepris, dans un milieu où cette thématique n'était pas très présente dans les débats publics, a débouché dans notre participation à plusieurs manifestations où nous avons eu l'occasion d'exposer les résultats de TropEmis et d'attirer l'attention sur l'urgence d'entamer la réflexion sur les adaptations possibles (Annexes 3 et 6, logiciel MorGwanik).

La suite du projet concerne notamment le couplage cité en V.3) car il devrait nous permettre de traiter le changement climatique à l'intérieur des systèmes agricoles dynamiques, dont l'évolution

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[2] Chopin, P., Doré, T., Guindé, L., Blazy, J.M., 2015. MOSAICA: A multi-scale bioeconomic model for the design and ex ante assessment of cropping system mosaics. Agricultural Systems 140, 26-39.

est fonction des enjeux locaux multiples (économiques, environnementales, politiques, sociales). En particulier, nous nous intéresserons à l'évaluation des cohérences et/ou divergences entre les stratégies d'atténuation et celles d'adaptation afin de favoriser l'adoption de solutions sans regret, notamment dans les systèmes émergents aux Antilles destinés à la production de biomasse.

Nous voulons terminer ce rapport en remerciant vivement Mme Marianna Martel, notre collègue de l'Ademe en Guadeloupe, pour son efficace collaboration dans la résolution de certaines difficultés logistiques apparues durant le projet.

Annexe 1

Dépliant TropEmis

Vos commentaires et questions :

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Projet TropEmis

Etude des pratiques de gestion de la matière organique dans les exploitations agricoles guadeloupéennes

Programme Reacctif - ADEME

Etude des pratiques de gestion de la matière organique en Guadeloupe

Définition et Constats

La **matière organique** du sol est composée d'organismes vivants, de résidus de végétaux et d'animaux et de produits en décomposition. Elle ne représente, en général, que quelques pourcents (0,5 à 10 %) de la masse du sol, et est composé à 58% de carbone.

L'intensification de l'agriculture est la principale cause de l'augmentation des émissions de gaz à effet de serre et de la réduction des stocks de carbone des sols dans les tropiques. Les Antilles françaises présenteraient cette même tendance, avec des diminutions de ses stocks.

Cette réduction pourrait s'accentuer dans les prochaines années à cause du changement climatique, ce qui affecterait la fertilité des sols

L'Etude

Déroulement et Objectifs

1. Sélectionner 520 parcelles sur tout le territoire pour représenter la diversité des systèmes
2. Réaliser 520 visites, enquêtes et collectes sur le terrain pour :
   - Identifier les systèmes de cultures et leur conduite
   - Déterminer les teneurs en carbone du sol
3. Analyse des résultats de l'enquête
4. Améliorer l'outil d'évaluation MorGw@nik, destiné à la profession agricole

Débouchés et Retombées

- **Formation à l'utilisation de l'outil MorGw@nik**
  http://toolsforagroecology.antilles.inra.fr/morgwanik/index.php/morgwanik/

INRA
MorGw@nik

- **Carte de la matière organique**

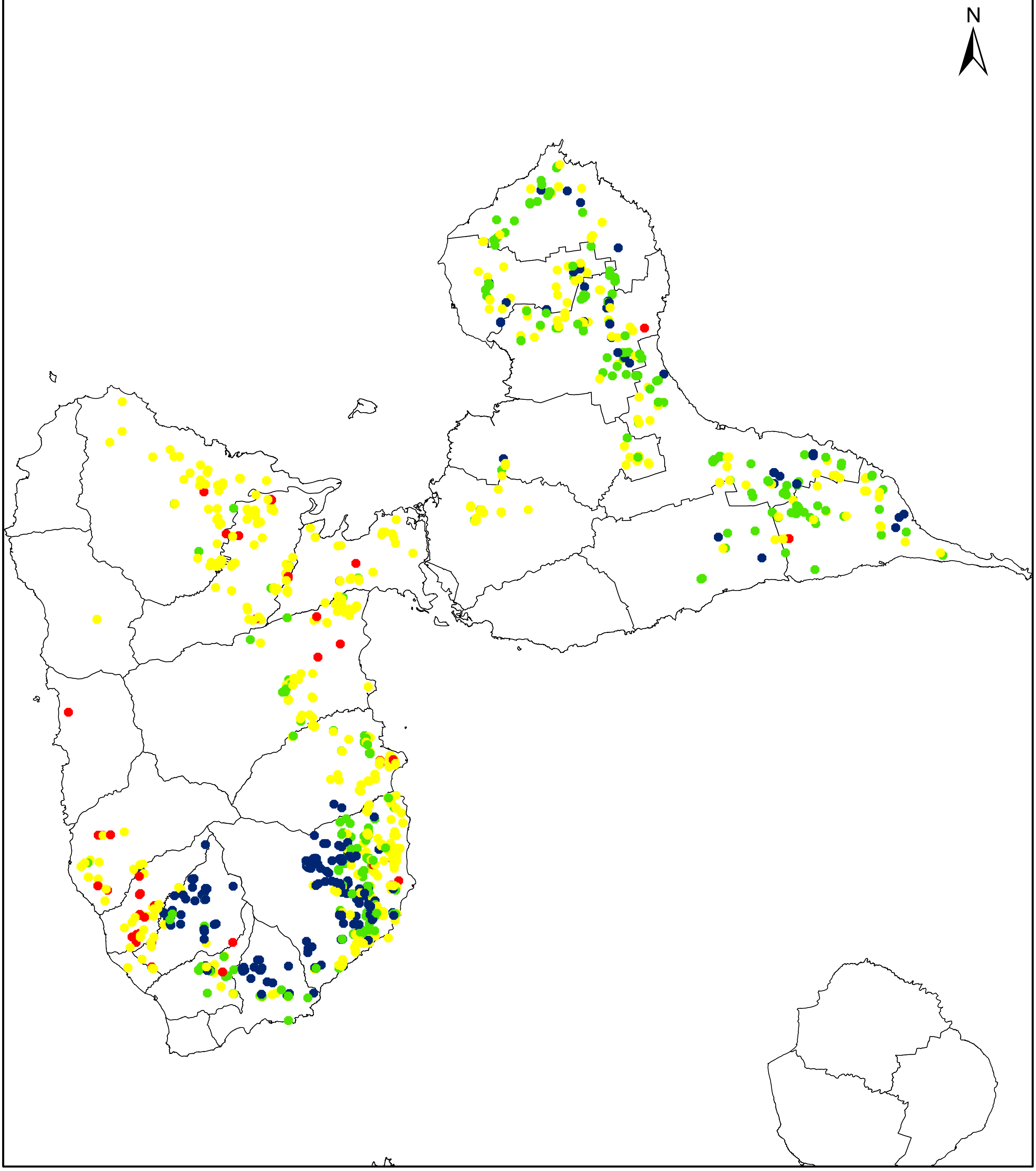
Annexe 2

Carte de carbone organique

Carbone Organique

Teneur en Carbone Organique

🔴 < 1,5 %
🟡 1,5 % - 2,49 %
🟢 2,5 % - 3,49 %
🔵 >= 3,5 %



Annexe 3

Diaporama de restitution finale

ADEME

Agence de l'Environnement et de la Maîtrise de l'Energie

Appel à projets REACCTIF

REcherche sur l'Atténuation du Changement ClimaTique par l'agrIculture et la Forêt

Antonio Bispo

Service Agriculture et Forêts – ADEME

02 41 20 43 07 – apr.reacctif@ademe.fr

ADEME

Agence de l'Environnement
et de la Maîtrise de l'Energie

Présentation nouvel APR REACCTIF

- **Rappels :**
  1. *Deux appels : 2011 & 2013*
  2. *Nbre total de projets retenus suite aux 2 appels : 24 + 5 en cours de signature*

- **Nouvel appel 2015 : mêmes objectifs mais nouvelles priorités**

- **Découpage en 4 thèmes (en 2015) :**
  1. *Flux de GES et stock de carbone (sols, cultures, élevage, forêts)*
  2. *Filières agricoles et forestières, de la production à la mobilisation*
  3. *Construire des stratégies à l'échelle des territoires*
  4. *Mettre en œuvre la transition écologique : approches économiques et sociales*

ADEME

Agence de l'Environnement et de la Maîtrise de l'Energie

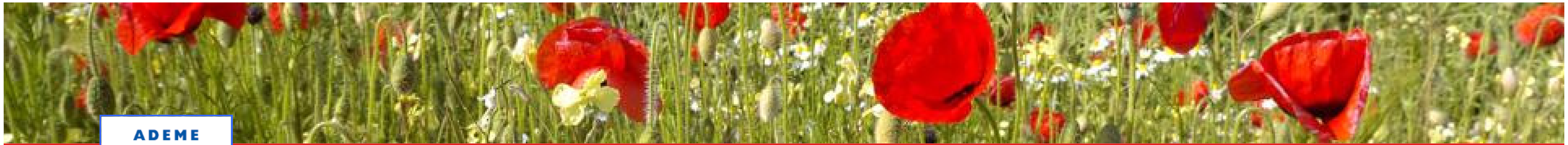
Nuage de mots clés

Animation et valorisation de l'APR

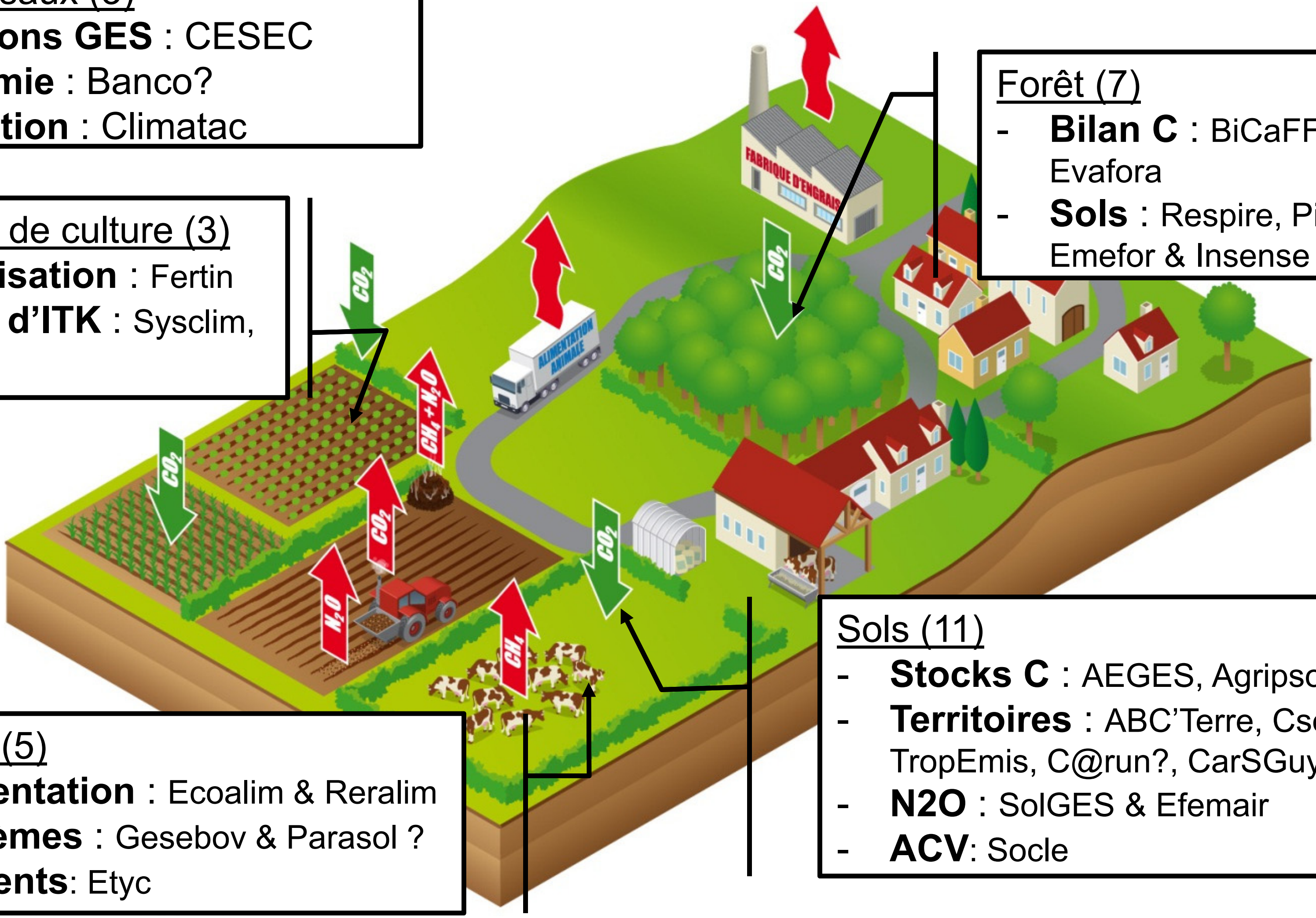
- **Animation des projets :**
  - *Séminaires tous les 18 mois environ avec les coordinateurs (et partenaires du projet), le jury de sélection, les équipes ADEME et les Ministères, Invités (ACTA, CITEPA…)*
    - Séminaire de lancement (Angers, avril 2013)
    - Séminaire décembre 2014 (lancement des projets 2013 et mi-parcours des projets 2011)
  - *Groupes thématiques se réunissant périodiquement :*

    2014 : Emissions de N_2O & stocks de C

    2015 : Forêt, ACV, valorisation (à programmer)
- **Valorisations collectives prévues**
  - *Guides, ouvrages, colloque, formations, normes…*
  - *Séminaires dédiés aux utilisateurs de la recherche (ex : APCA, MAAF, CIAG ?)*



Positionnement des projets en cours



Transversaux (3)
- **Emissions GES** : CESEC
- **Economie** : Banco?
- **Perception** : Climatac

Système de culture (3)
- **Fertilisation** : Fertin
- **Bilan d'ITK** : Sysclim, CiCC

Forêt (7)
- **Bilan C** : BiCaFF, Gesfor & Evafora
- **Sols** : Respire, Picaso, Emefor & Insense

Elevage (5)
- **Alimentation** : Ecoalim & Reralim
- **Systèmes** : Gesebov & Parasol ?
- **Effluents**: Etyc

Sols (11)
- **Stocks C** : AEGES, Agripsol, P2C?
- **Territoires** : ABC'Terre, Csopra, TropEmis, C@run?, CarSGuy?,
- **N2O** : SolGES & Efemair
- **ACV**: Socle

Priorités affichées pour 2015

- **La mobilisation de la biomasse forestière et agricole, que ce soit sur les aspects biophysiques, organisationnels, économiques et sociétaux,**
- **Les projets en sciences économiques et sociales visant à favoriser et à accompagner la transition de l'agriculture et de la forêt.**
- **L'évaluation des cohérences et/ou divergences entre les stratégies d'atténuation et celles d'adaptation afin de favoriser l'adoption de solutions sans regret,**
- **Les travaux réalisés à l'échelle des territoires ou des filières, intégrant notamment la notion d'économie circulaire.**

2015

Année internationale
des sols

http://www.fao.org/soils-2015

Programme ADEME REACCTIF– REcherche sur l'Atténuation du Changement ClimaTique par l'agrIculture et la Forêt

Evaluation régionalisée de l'EMISsion et de la séquestration de carbone dans les sols TROPicaux de Guadeloupe (TROPEMIS)

J. Sierra, F. Causeret, J.L. Diman, M. Publicol, L. Desfontaines,
A. Cavalier, F. Solvar, F. Germain, D. Denon
(Unité ASTRO / INRA Antilles-Guyane)
D. David
(Carib Agro)

projet financé par

Plan

- *Objectifs et enjeux*
- *Définitions*
- *Démarche*
- *Résultats*
    - *Carte de matière organique (MO)*
    - *Utilisation d'amendements*
    - *Estimation du bilan de MO par région et par Système de Culture (SdC)*
    - *Relation MO et chlordécone (CLD)*
    - *Impact du Changement Climatique (CC)*
    - *Réduction de l'impact du CC*
- *Conclusions et perspectives*

Objectifs et enjeux

Contexte

- ✓ Perte de matière organique dans l’agriculture de diversification ?
- ✓ Quel impact du CC ? Quelle adaptation ?
- ✓ Que faire des déchets organiques ?

Objectifs

- ✓ Analyser l'impact du milieu (sol, climat, SdC) et du CC sur les émissions de C à l'échelle du territoire, et identifier les pratiques qui favorisent leur réduction

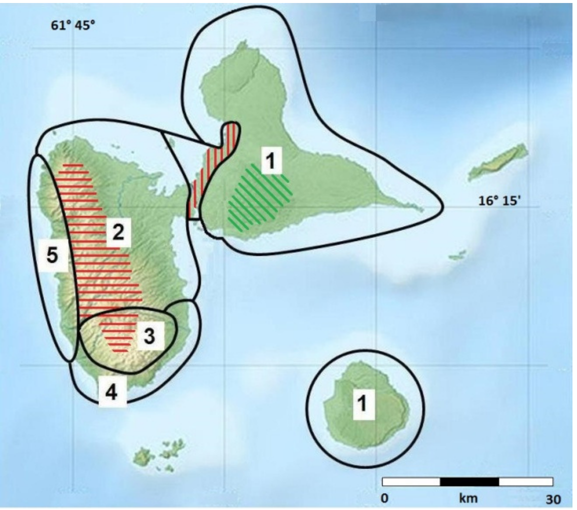
  * Résultats attendus :

  - hiérarchisation des variables explicatives
  - calibration et validation du modèle MorGwanik

  * Objet :

  - sols agricoles, émissions de C

Régions pédoclimatiques



Echelle

- ✓ Spatiale : territoire
- ✓ Temporelle : 15 ans vers le passé, 30 ans vers l’avenir

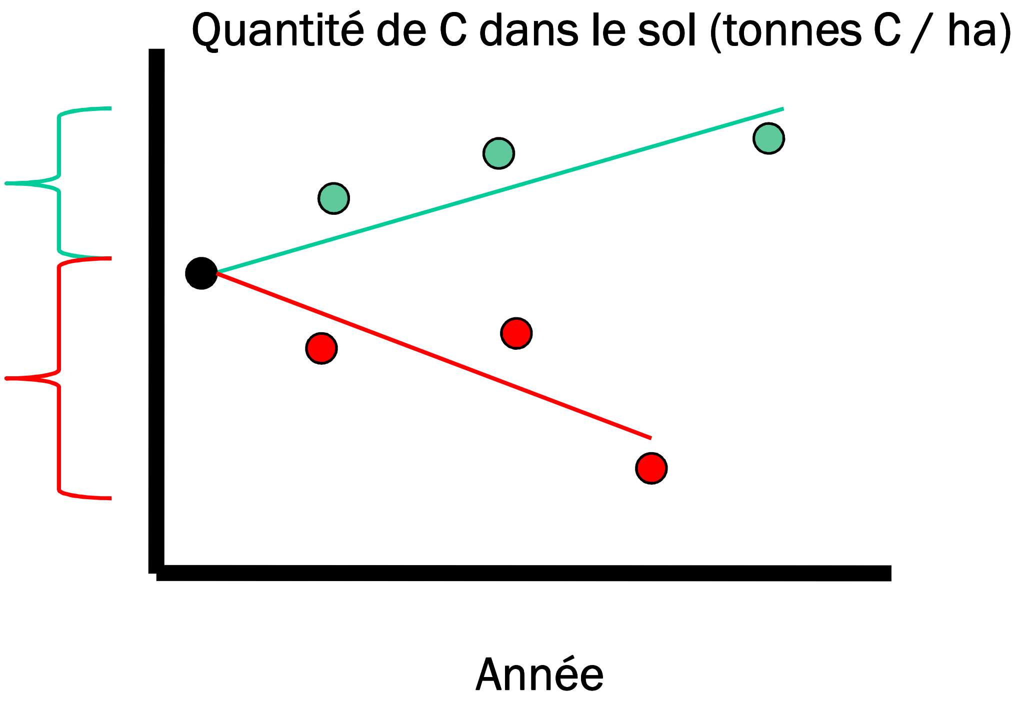
Définitions

$MO \approx C \times 2$

augmentation = <u>séquestration</u>

diminution = <u>émission</u>

<u>Gaz à effet serre (GES)</u>



Démarche : bilan de MO

Quantité ➔ *terrain*
Humification ➔ *laboratoire*
Impact du CC ➔ *Climator & Météo France*

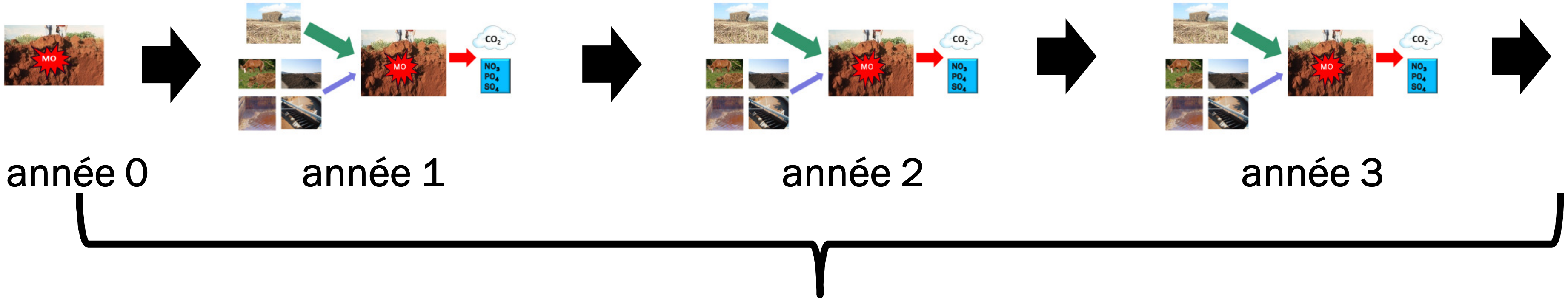
NO_3
PO_4
SO_4

Stock C
➔ *BdD Carib Agro*
➔ *470 prélèvements*

Minéralisation (région et SdC)
* *travaux INRA & modélisation*
* Impact du CC ➔ *Climator & Méteo France*

Quantité ➔ *470 enquêtes*
Humification ➔ *laboratoire*

Démarche : rotations



année 0 année 1 année 2 année 3

Rotations ➔ *470 enquêtes*

* succession des cultures

* rendements

* gestion des résidus

* gestion d'amendements

MorGwanik

http://toolsforagroecology.antilles.inra.fr/morgwanik

Démarche : les régions et les systèmes de culture

Situations analysées :

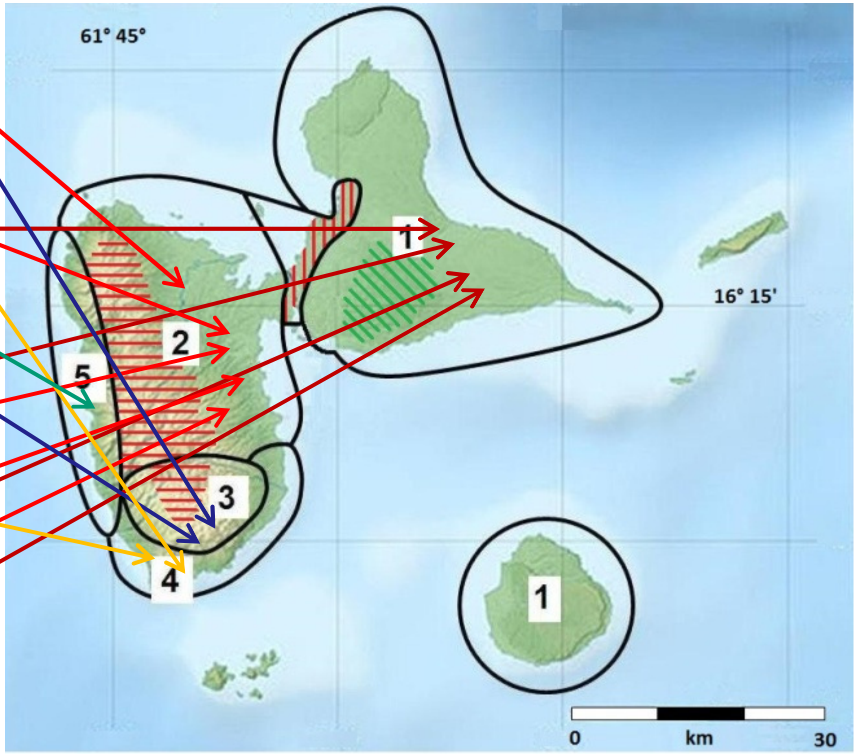
Banane (monoculture) andosol (37)
Banane (monoculture) ferralsol (26)
Banane (monoculture) nitisol (11)
Verger vertique (10)
Canne (monoculture) ferralsol (7)
Canne (monoculture) vertisol (26)

exportation & verger : 117

Maraîchage (rotation) andosol (15)
Maraîchage (rotation) vertisol (24)
Maraîchage (rotation) ferralsol (2)
Maraîchage (rotation) nitisol (2)
Ananas (rotation) ferralsol (49)
Melon (rotation) vertisol (20)
Igname (rotation) ferralsol (8)
Igname (rotation) vertisol (16)

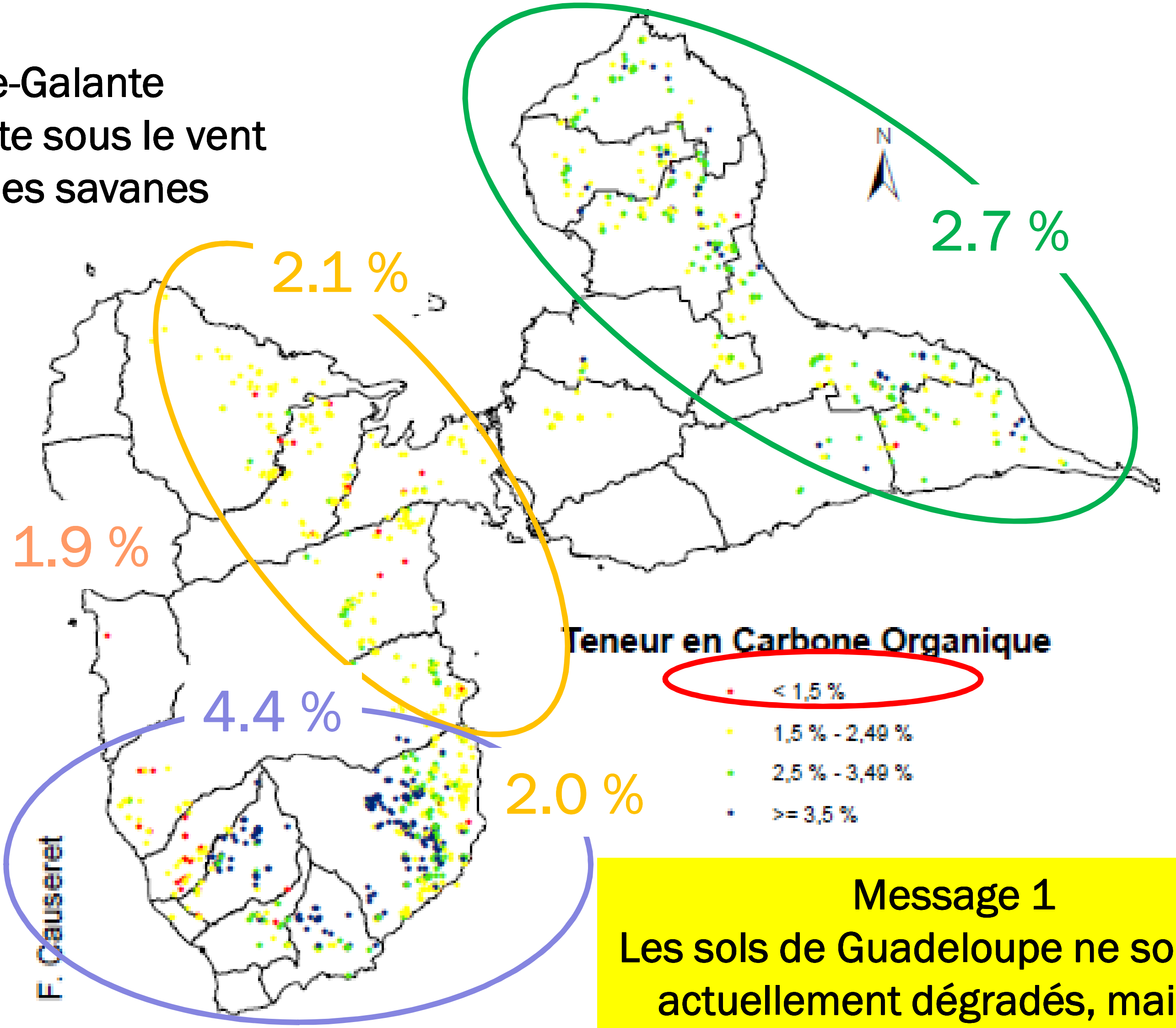
diversification : 136

total : 253



Résultats : Carte de MO

- 1200 parcelles
- Pas d'info sur Marie-Galante
- Peu d'info sur la Côte sous le vent
- Très peu d'info sur les savanes



F. Causeret

Message 1
Les sols de Guadeloupe ne sont pas actuellement dégradés, mais …

Résultats : utilisation d’amendements

Système de culture	Parcelles amendées (%)	Dose (tonne équiv. compost / cycle / ha)
banane	30	50
canne	75	9
ananas	20	30
igname	35	60
melon	5	55
maraîchage	60	100

Pour toute la Guadeloupe :

21 000 tonnes / an

1 tonne / ha / an

(surestimation possible)

Résultats : utilisation d’amendements

Accueil > Presse > Communiqués > **Contribution de l'agriculture à la lutte contre le changement climatique : (...)**

Communiqués

Contribution de l’agriculture à la lutte contre le changement climatique : Stéphane LE FOLL annonce le lancement d’un projet de recherche international : le « 4 pour 1000 »

Paris
17/03/2015

Fil actualités

19/05 Le retour en formation pour les 16-25 ans : un nouveau départ dans la vie #ReviensTeFormer (revienste former.gouv.fr)

19/05 Projet de reconfiguration du capital de Doux autour de Terrena et Sofiprotéol : Stéphane Le Foll salue les perspectives pour la filière volaille française

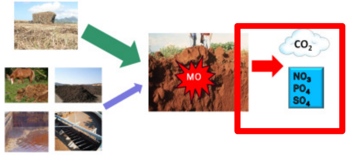
* Les sols du monde contiennent 2400 milliards de tonnes de C
* Les émissions de GES représentent 8.9 milliards de tonnes de C / an ➔ 4 ‰ du stock C

* Les sols agricoles de Guadeloupe contiennent 80 t C / ha

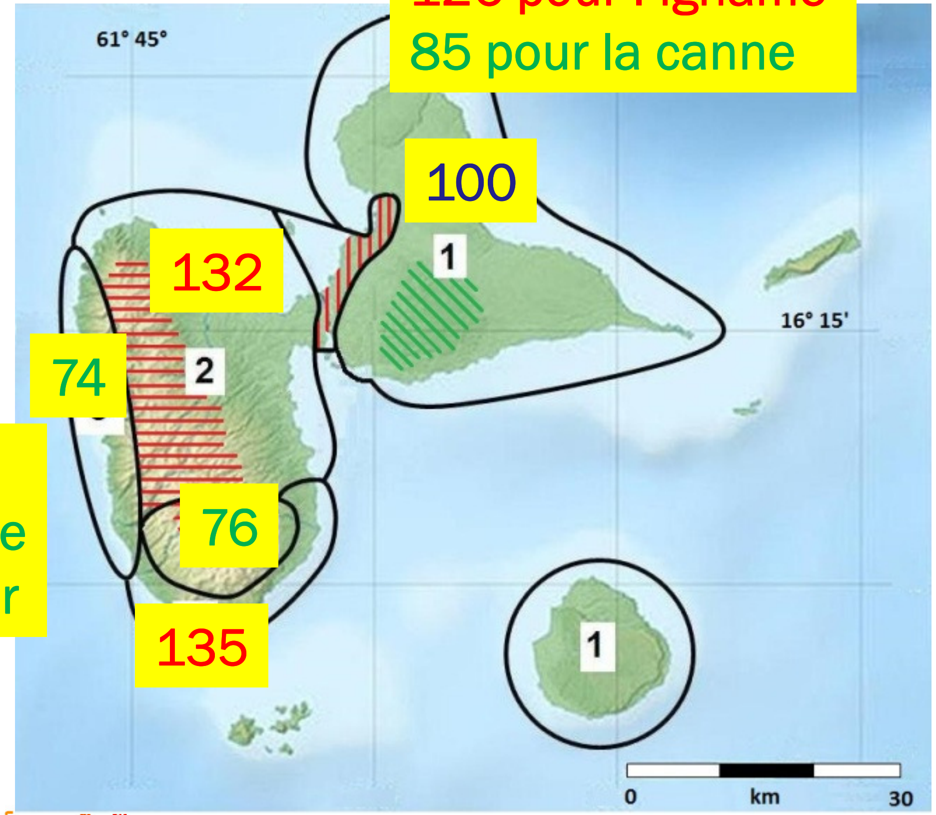
* 4 ‰ représentent environ 0.3 t C / ha / an

➔ 3.8 tonnes compost / ha /an

Résultats : taux d'émission de C par région et SdC



Effet du sol et du climat



126 pour l'igname
85 pour la canne

100

132

74

16 pour le verger

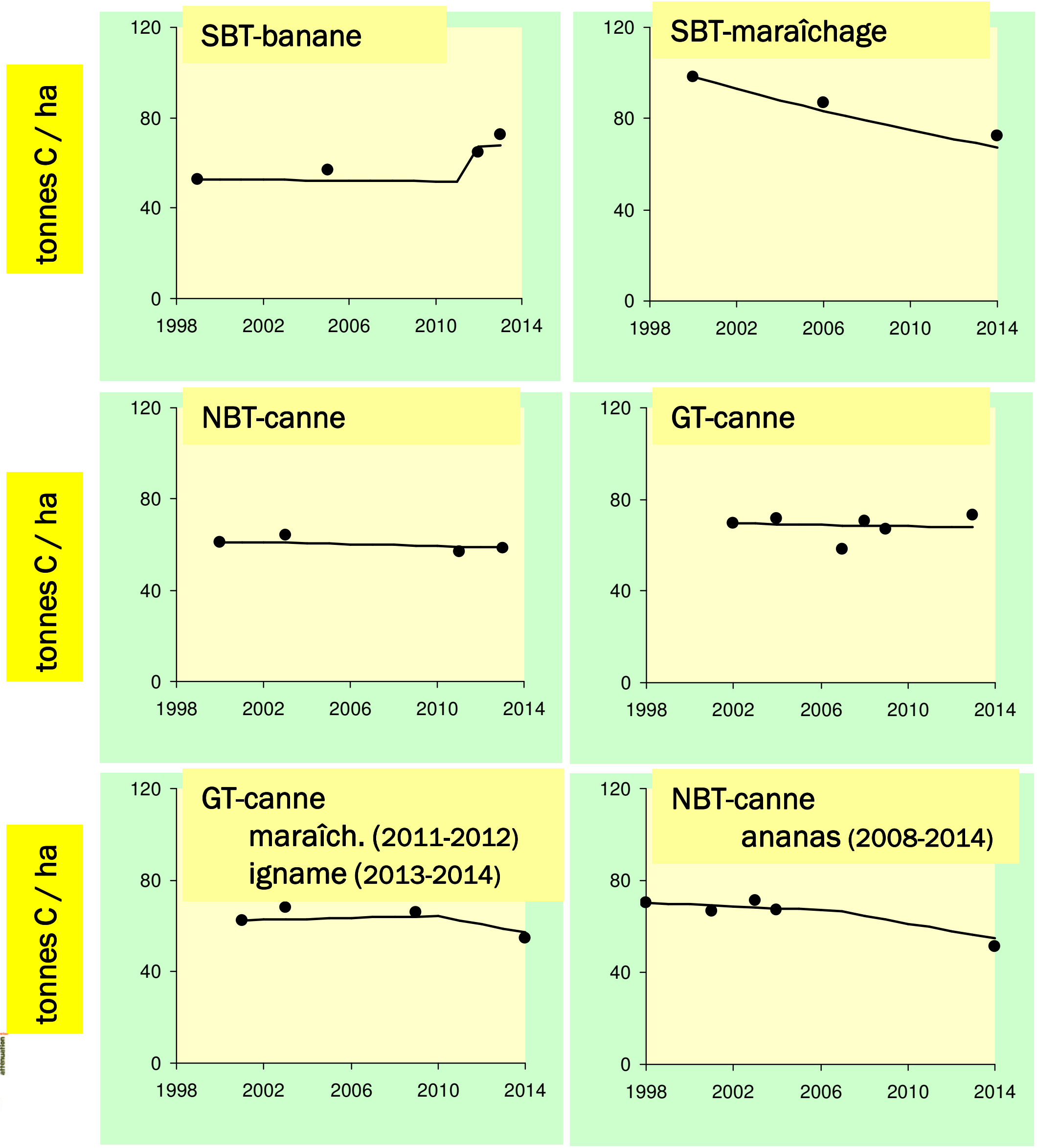
76

135

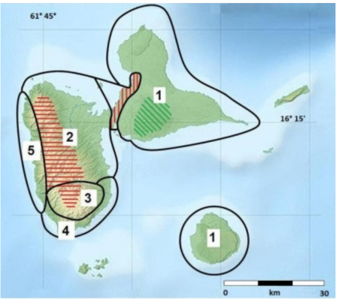
Effet du SdC

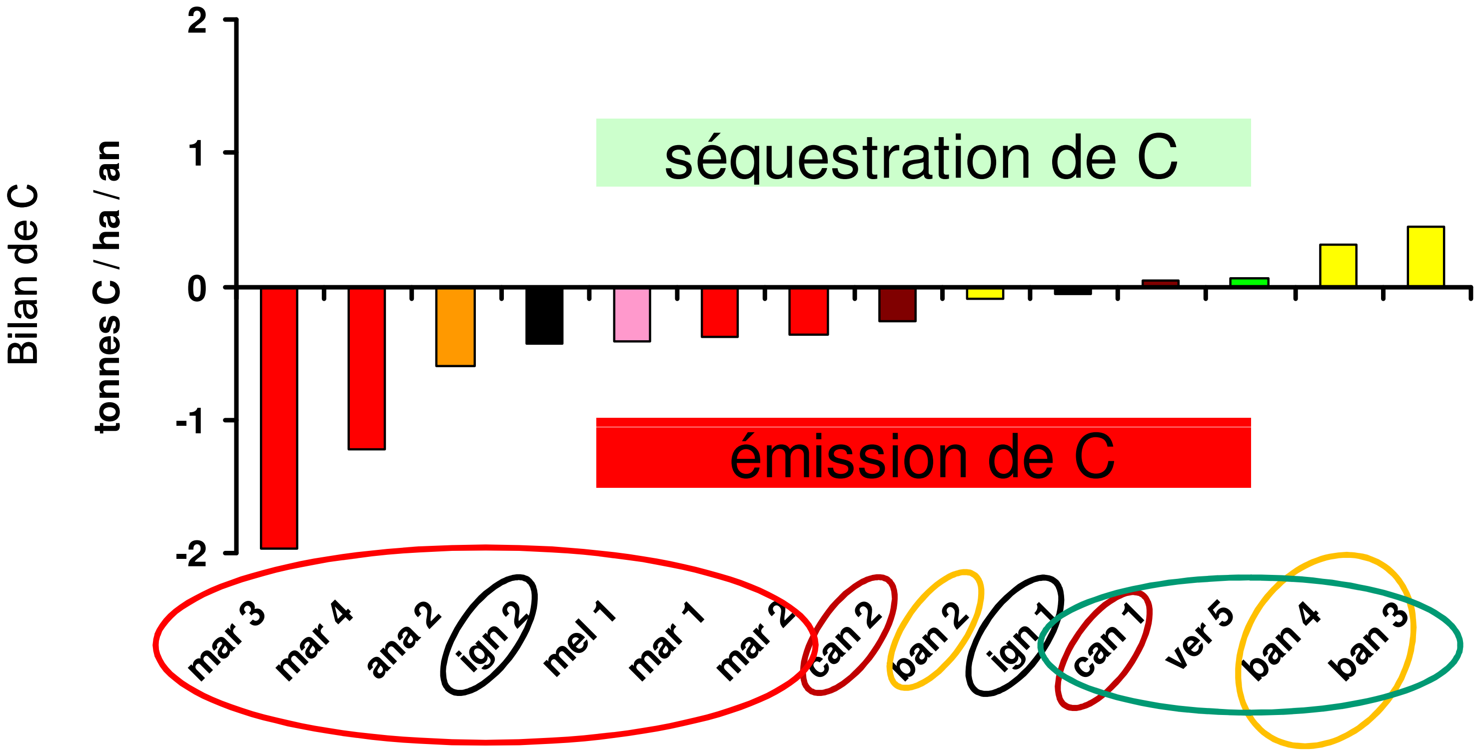
culture	facteur de correction
verger	0.22
canne	0.85
ananas	0.95
igname	1.26

Résultats : évolution de la MO



Résultats : bilan de C par SdC

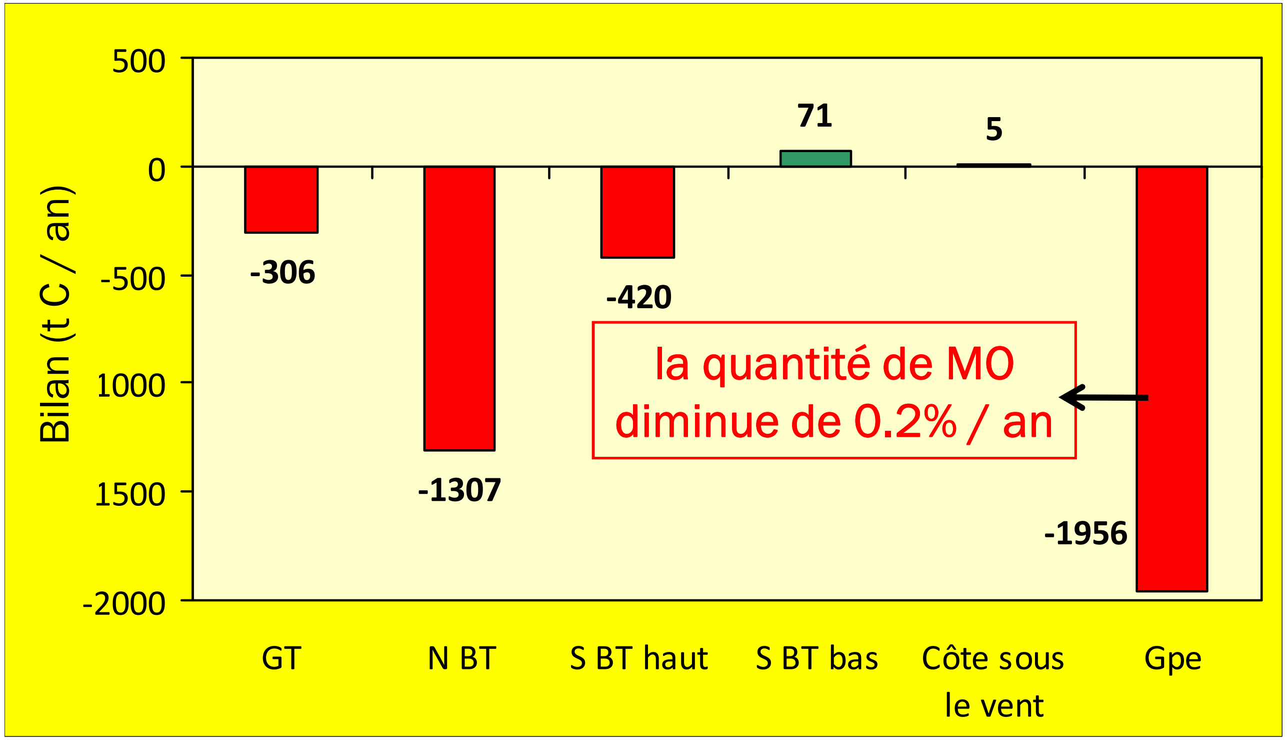




L'effet du SdC est plus important que celui de la région

Message 2
La MO peut être
conservée voire améliorée

Résultats : bilan par région



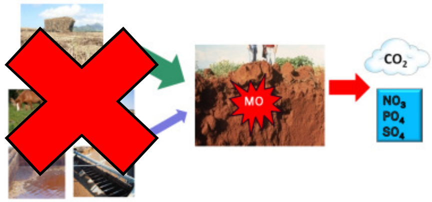
la quantité de MO diminue de 0.2% / an

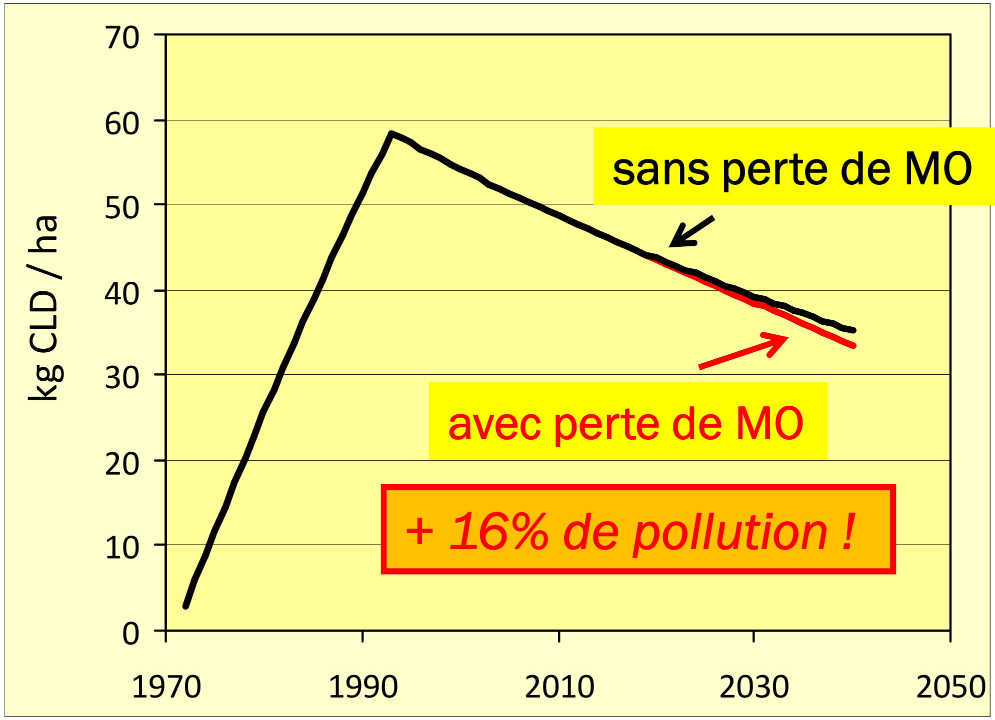
Message 3
N BT : région prioritaire

Avez-vous des questions ?

Résultats : relation MO et CLD

Exemple en S BT : changement de système en 2015 qui entraîne une réduction de la teneur en matière organique (p.ex. production de biomasse)





sans perte de MO

avec perte de MO

+ 16% de pollution !

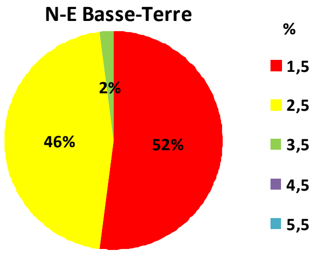
Message 4
Il faut tenir compte que la MO retient la chlordécone !

ADEME
Agence de l'Environnement et de la Maîtrise de l'Energie

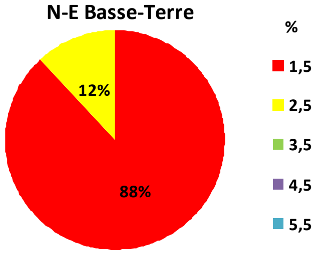
INRA SCIENCE & IMPACT

CaribAgro
Agronomie – Développement durable

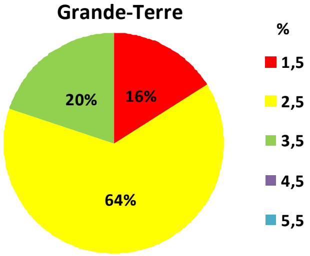
Résultats : impact du CC



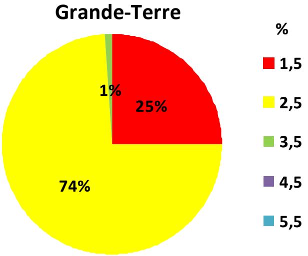
2010



2040



2010



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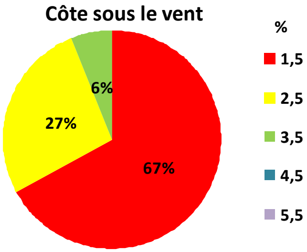
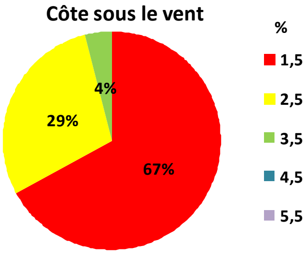


2010



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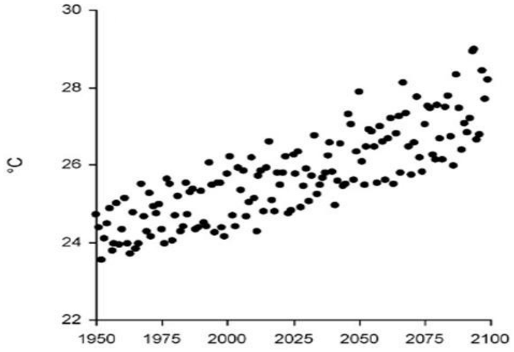
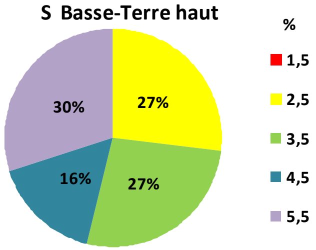
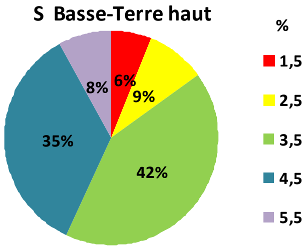


Météo France, 2010



2010



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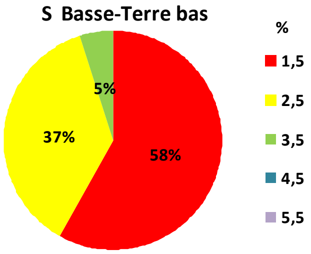
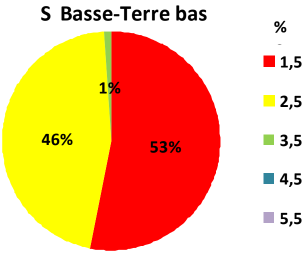


2010



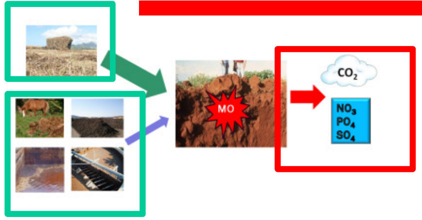
2040

ADEME
Agence de l'Environnement et de la Maîtrise de l'Energie

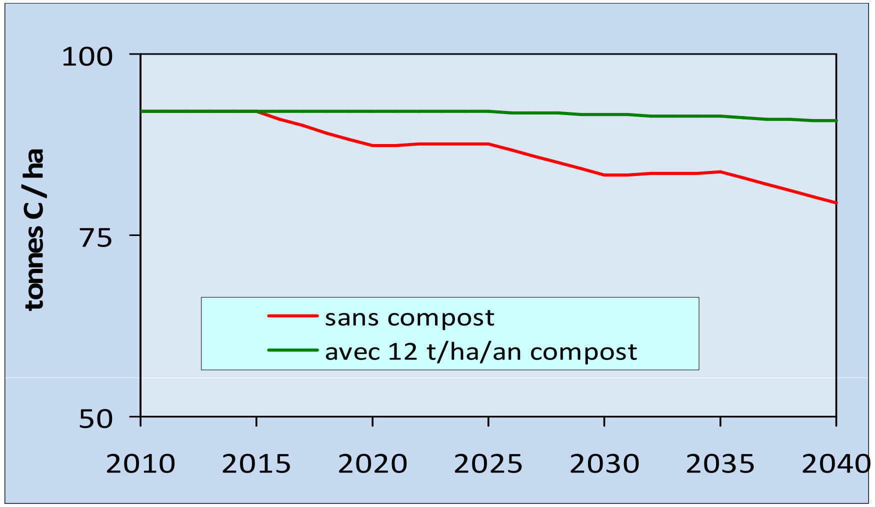
INRA SCIENCE & IMPACT

CaribAgro
Agronomie – Développement durable

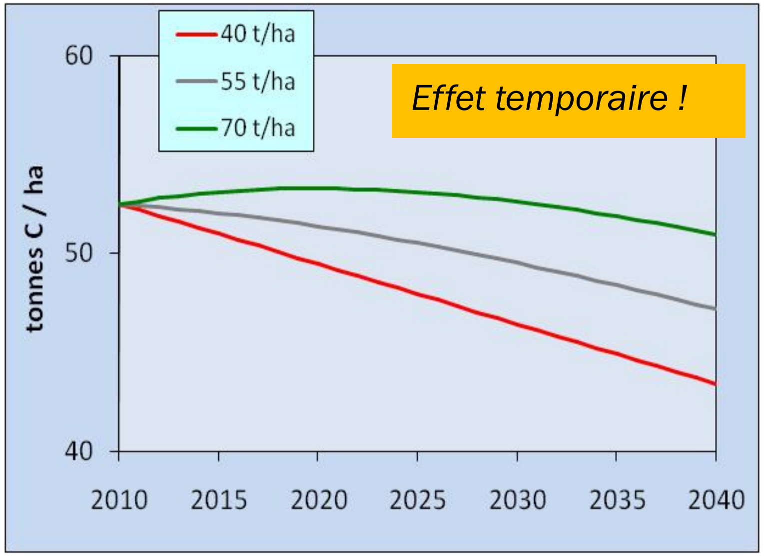
Résultats : réduction de l'impact du CC



Effet direct : apporter un compost
Cas de la banane/maraîchage en S BT

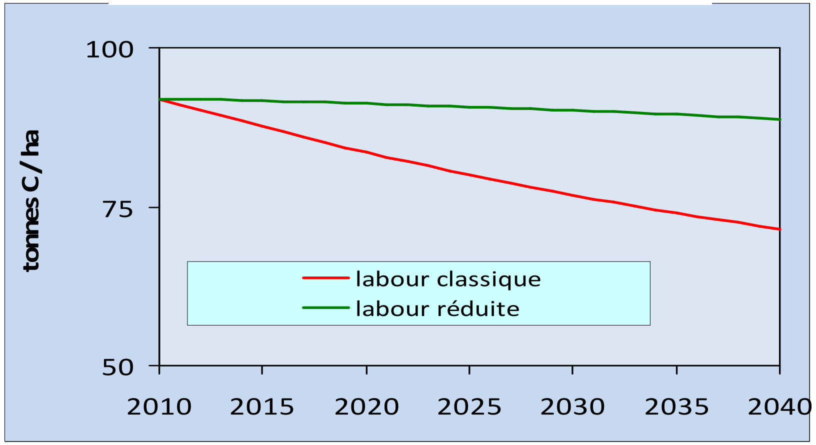


Effet indirect : augmenter les rendements
Cas de la canne au N BT (chaulage)



Effet temporaire !

Effet direct : réduire le travail du sol
Cas du maraîchage en S BT



Résultats : réduction de l'impact du CC

Estimation de la quantité d'amendements nécessaire pour compenser l'impact du CC

Utilisation actuelle		21 000 t éq. compost / an
Pertes par CC	3 800 t C / an	
Pour combler ces pertes		51 000 t éq. compost / an
Besoin en amendement		72 000 t éq. compost / an

Message 5
L'impact (*très fort = -0.4% / an)* du CC peut être géré dans le moyen terme ➔ combinaison des pratiques

Message 6
Adaptation des politiques incitatives

Conclusions & perspectives

* Présent

pas dramatique …

mais il faut organiser l'adaptation

notamment au nord BT et pour la diversification

➔ *établir des priorités*

* Futur très proche

développer et pérenniser la filière « amendements »

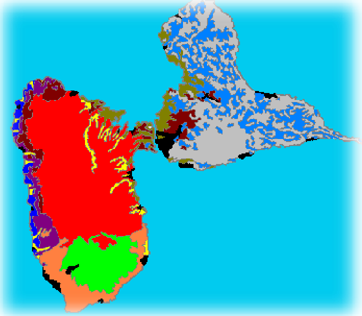
➔ *concurrence entre filières*

développer et pérenniser l'analyse des sols

➔ *une fois tous les 5 ans*

évaluation participative des pratiques

➔ *il n'y a pas UNE solution*



* Pourquoi pas ?

transformer la Guadeloupe dans un cas d'étude de la Caraïbe

Merci de votre attention !

Annexe 4

Synthèse des résultats

Programme ADEME REACCTIF

(REcherche sur l'Atténuation du Changement ClimaTique par l'agrIculture et la Forêt)

Projet TropEmis (2013-2015)

(Evaluation régionalisée de l'EMISsion et de la séquestration de carbone dans les sols TROPicaux de Guadeloupe)

Responsable scientifique : **J. Sierra (Unité AgroSystèmes Tropicaux, INRA Antilles-Guyane)**
Collaboration : **D. David (Carib Agro)**

Synthèse des résultats

L'objectif était ...

... d'analyser l'impact du milieu (sol, climat, système de culture) et du changement climatique sur les émissions de carbone (perte de matière organique, MO) à l'échelle du territoire, et d'identifier les pratiques qui favorisent leur réduction

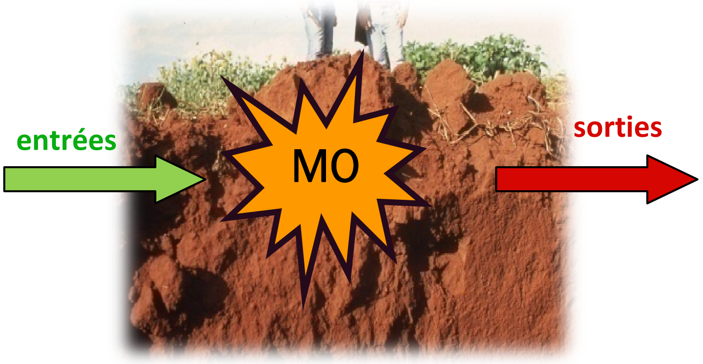
TropEmis c'était ...

- ❖ ... 469 enquêtes et analyses des sols réalisées chez les agriculteurs
- ❖ ... 253 parcelles suivies et évaluées depuis 1998 dans toutes les régions pédoclimatiques de la Guadeloupe
- ❖... 14 systèmes de culture analysés (cultures d'exportation et diversification)
- ❖... 7 résidus de cultures et 4 amendements organiques utilisés en Guadeloupe analysés en laboratoire pour évaluer leur impact sur la MO
- ❖... un scénario de changement climatique élaboré par Météo France appliqué à la Guadeloupe
- ❖ ... la valorisation de la base de données de sol de Carib Agro unique dans la Caraïbe (6000 analyses de sol) (1998-2013)
- ❖ ... la calibration du modèle MorGwanik afin évaluer l'impact du changement climatique en Guadeloupe
- ❖... la mise en ligne de MorGwanik pour l'aide à la décision

Les cinq régions pédoclimatiques de Guadeloupe

La teneur en MO est le résultat d'un bilan ...

- ❖ ... entre des entrées de MO (résidus de cultures et amendements organiques),
- ❖ et des sorties de MO (décomposition de la MO par les microorganismes du sol).
- ❖ un bilan nul = le sol est en équilibre
- ❖ un bilan négatif = le sol se dégrade et produit des gaz à effet de serre (GES)
- ❖ un bilan positif = le sol s'enrichit en MO (séquestration de carbone)



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2015
Année internationale
des sols

Etat des lieux

❖ Le stock actuel de MO dans les sols de Guadeloupe (moyenne 70 tonnes MO/ha dans la couche de 0-30 cm) est correct mais la tendance depuis 1998 est à la diminution

❖ Les sols les plus pauvres en Guadeloupe (<1.5% de carbone, voir la carte) sont plutôt riches comparés à la plupart des sols tropicaux

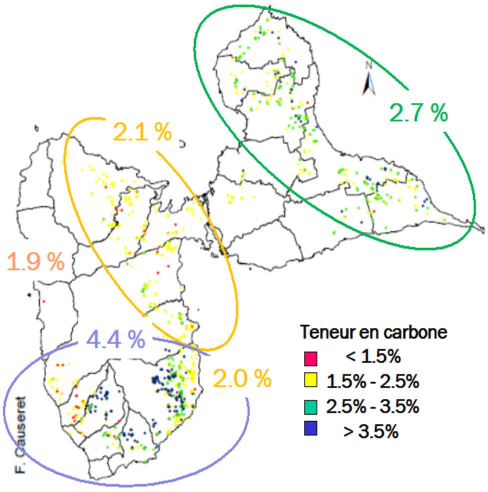
❖ Malgré cela, la Guadeloupe perd en moyenne 1% de son stock en MO tous les 5 ans depuis 1998

❖ Le nord Basse-Terre est la région qui perd le plus de MO : 1% de son stock tous les 2 ans et demi !

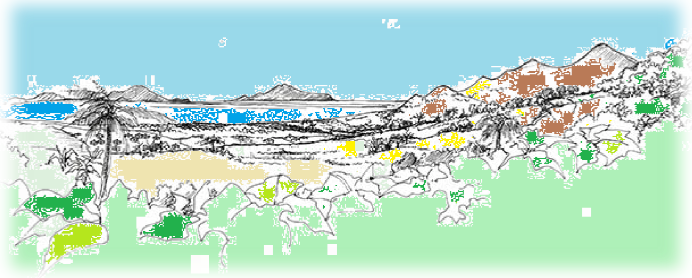
❖ La Côte sous le vent est la région qui perd le moins de MO : 1% tous les 25 ans !

❖ La dose d'amendement organique moyenne appliquée est faible : 1 tonne/ha/an

☞ ***les pertes de MO sont liées au changement climatique mais aussi à un travail du sol intensif dans certains systèmes de culture***



Rappel :
teneur en MO = teneur en carbone x 2



L'impact des cultures

❖ Les pertes de MO les plus importantes sont observées en diversification (moins de résidus de culture, labours plus intensifs), notamment au sud Basse-Terre : jusqu'à 1% du stock par an !

❖ Les cultures d'exportation ont tendance à conserver ou à augmenter les teneurs en MO

L'impact du changement climatique

❖ Le changement climatique accélère les pertes : la Guadeloupe perdra 1% de son stock de MO tous les 2 ans et demi d'ici à 2040, notamment en diversification mais aussi dans le bassin cannier du nord Basse-Terre

Conclusions

❖ La situation actuelle n'est pas dramatique mais il faut déjà organiser l'adaptation au changement climatique

❖ Il faudrait établir des priorités pour les actions d'adaptation : nord Basse-Terre et cultures de diversification

❖ Quelques pratiques pour l'adaptation : réduire le travail du sol, doubler l'utilisation des amendements organiques, revenir sur la pratique du chaulage en nord Basse-Terre

Pour finir

❖ Les sols doivent être analysés tous les 5 ans afin de contrôler l'impact du changement climatique

❖ Il faut organiser une évaluation participative des pratiques d'adaptation (profession agricole, collectivités, recherche)

❖ La Guadeloupe est bien positionnée pour participer au Programme "4 pour 1000" du Ministère de l'Agriculture afin d'augmenter la séquestration de carbone dans les sols

Participants à TropEmis :
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Annexe 5

Article scientifique : "Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe"

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Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe

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A B S T R A C T

Export agriculture in the Caribbean is often blamed for pollution of soils and water resources. At the same time, the reduction of preferences in the international markets for major agricultural exports from the Caribbean induced a partial reorientation of the agriculture towards the local markets, which included crop diversification. This study was carried out to assess the sustainability of that agricultural switch with respect to maintaining, increasing or decreasing soil organic carbon (SOC) stocks. We analysed the impact of export crops (sugarcane and banana monocultures) and diversified agriculture (as monoculture or in rotation with export crops) on SOC stocks using the case study of Guadeloupe (Lesser Antilles). Agriculture in Guadeloupe involves a mosaic of soils, climates, crops and farming practices, which well represent the tropical conditions of export and diversified agriculture in the region. The study was based on: (i) a soil database including information on the SOC stocks of numerous cropping system—agro-ecological region (AER) situations, (ii) a survey of farming practices performed on a network of 382 farmers (e.g. crop rotations and yields, management of residues and organic amendments), and (iii) the development of a simple model of annual C inputs and outputs to assess SOC dynamics at the AER scale. The model was calibrated and evaluated using 253 plots and included 827 SOC measurements selected from the soil database. The model produced satisfactory estimates of changes in SOC stocks and provided an explanation for differences between cropping systems and AERs in terms of the C inputs and outputs. While sugarcane and banana monocultures were able to preserve or increase SOC, diversification was likely to reduce it. These differences were due to higher C inputs from crop residues together with lower C outputs for export agriculture. Lower SOC outputs by mineralization were mainly associated with the longer cycle of these pluriannual crops (5 yr), which decreased the impact of soil tillage at planting. Banana monoculture in the most humid AERs was the only cropping system that displayed a clear pattern of C sequestration (+0.5 Mg C ha^{-1} yr^{-1}). The highest SOC losses were observed with vegetable crops in the same AERs (e.g. −2.0 Mg C ha^{-1} yr^{-1}). Calculations made using the model indicated that the sustainability of diversified agriculture in the Caribbean might be reinforced by adopting reduced soil tillage, organic amendments and the liming of the more acid soils to increase yields and crop residues. The results of this study suggest that the implementation of new agricultural policies to reduce the negative environmental impacts of export crops should involve measures to preserve their positive effect on SOC storage.

1. Introduction

Agriculture in the island states of the Caribbean is currently facing crucial challenges because of the impact of trade liberalisation and the reduction or elimination of preferences for major agricultural exports in most international markets (United Nations, 2013). Moreover, because of the overuse of chemical fertilizers and pesticides, the sustainability of export agriculture is often questioned with respect to soil contamination and the pollution of coastal resources, such as fresh and sea water, flora and fauna (Castillo et al., 2006; Cabidoche et al., 2009). At the same time, the regional food import market is large and growing due to increases in population and tourism (FAO Subregional Office for the Caribbean, 2013). In this context, that FAO Office proposed that a significant proportion of Caribbean agriculture should be reoriented towards domestic markets in order to ensure a competitive replacement for imports as a means of enhancing food security in the region. To achieve this, it is necessary to use more sustainable cropping systems, as compared with monoculture production for export,

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including crop diversification and rotation, organic farming, the use of manure and composts and the application of land conservation practices (IFAD, 2014).

Although crop diversification and rotation in the Caribbean are increasingly being seen as credible alternatives to conventional agriculture based on monocultures of banana and sugarcane, a major agro-environmental concern regarding such a switch involves the impact of cropping systems on SOC stocks (IFAD, 2014). SOC stocks change in response to the balance between C inputs and outputs. For agricultural soils, inputs are driven primarily by the recycling of crop residues and external additions of C such as organic amendments, while outputs are largely driven by the rate of microbial decomposition of SOC, this being affected by climate, land use and soil tillage (Smith et al., 2012). In the Caribbean, diversification based on vegetable or tuber crops might affect SOC stocks because the mass of crop residue recycling in soil is smaller and soil tillage is more intensive than with export crops (Zinn et al., 2005; Lal, 2008). This picture may vary in soils under organic agriculture because using relatively high rates of organic amendments increases C inputs (Lal, 2004). As in other tropical regions (Milne et al., 2007), the paucity of data on changes in SOC stocks in the Caribbean is a significant limitation to a more comprehensive and quantitative assessment of the impact of crop diversification and rotation on the sustainability of these alternative cropping systems. There is therefore an urgent need to develop and implement models of SOC dynamics that can be applied at relatively small spatial scales (e.g. agro-ecological regions (AER) of 10^2–10^3 km^2 in the Caribbean) so as to facilitate decision making in the agricultural sector.

This paper presents an experimental and modelling approach designed to assess the impact of crop diversification and rotation on SOC stocks in the Caribbean, based on a case study in Guadeloupe. Guadeloupe is a French Overseas Department that has a long history of cultivation going back hundreds of years, while modern agriculture was introduced forty years ago following the green revolution. The main issue affecting this switch has been that of the intensification of agricultural land use and, more recently, changes in cropping patterns which involved the partial conversion of sugarcane and banana monocultures to rotations including crops for the domestic market (Agreste, 2011). Guadeloupe is unique in the Caribbean for three reasons: (i) in a relatively small territory of 1600 km^2 it presents a great diversity of soils and climates that are representative of most of the agro-ecological conditions encountered in the Caribbean region (Cabidoche et al., 2004), (ii) it also covers a large range of land uses from monocultures for export to more diversified systems including roots and tuber crops, orchards and vegetable crops (Clermont-Dauphin et al., 2004), and (iii) the SOC stocks of many soils in different AER and under different cropping systems have been analysed since 1998, and the georeferenced data has been structured in a software application that is simple to operate for modelling purposes. This database is also unique in that it brings together both farm and regional scale information on several variables that determine SOC stocks.

The objective of this study was therefore to assess the impact of crop diversification and rotation on SOC stocks in tropical soils of the Caribbean, based on the case study of Guadeloupe. For this we developed a simple model of C inputs and outputs which was calibrated and tested using experimental data obtained from plots included in the soil database. The data covered a broad range of soil types, climates and cropping systems. In contrast to complex models of SOC dynamics, a simple model requires minimal data inputs and few parameters and is therefore well suited to situations with scarce agricultural data, such as in the Caribbean. Data concerning crop yields and farming practices (rotation,

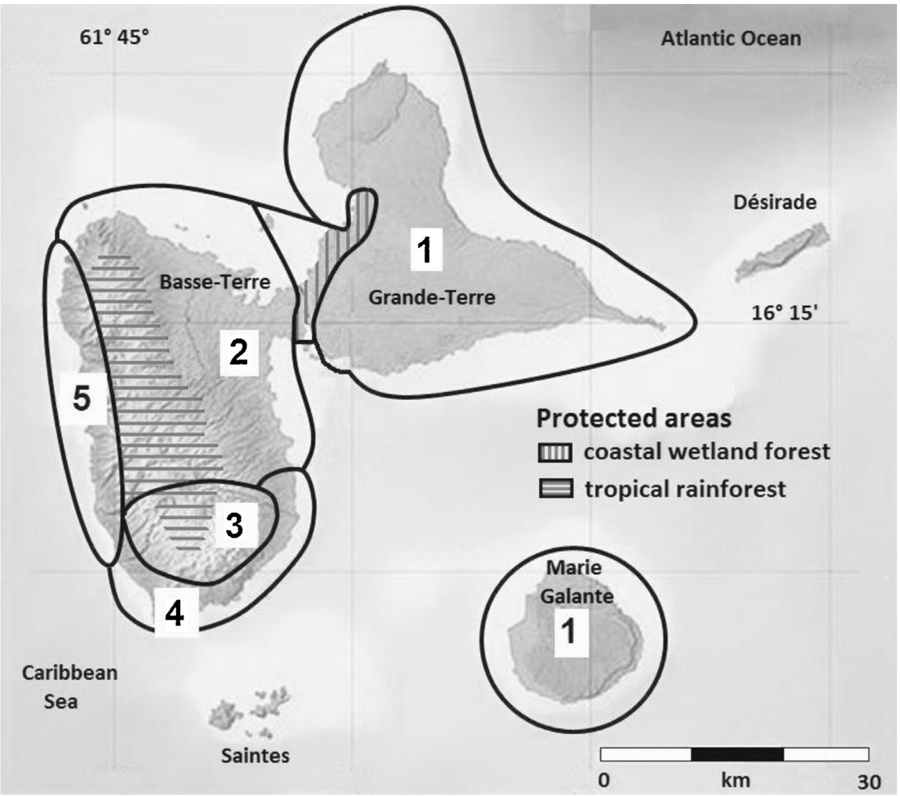

Fig. 1. The archipelago of Guadeloupe and its five agro-ecological regions (AER). Soils are vertisols in AERs 1 and 5, ferralsols in AER 2, andosols in AER 3 and nitisols in AER 4. Mean rainfall is 1100 mm yr^{-1} in AER 1, 2300 mm yr^{-1} in AER 2, 3800 mm yr^{-1} in AER 3, 2200 mm yr^{-1} in AER 4, and 900 mm yr^{-1} in AER 5. Mean air temperature varies from 23.9 °C in AER 3 to 26.6 °C in AER 5.

management of crop residues and organic amendments) were collected during a survey performed for this study. After calibration and evaluation, the model was applied to simulate the effects of crop diversification and changes in farming practices on SOC stocks.

2. Material and methods

2.1. Study location, soils and climate

The study was carried out in Guadeloupe, which is located in the Lesser Antilles in the eastern Caribbean Sea (Fig. 1). Guadeloupe has a population of 408,000 and is an archipelago consisting of three main islands (Basse-Terre: 848 km^2; Grande-Terre: 586 km^2 and Marie-Galante: 158 km^2) and several smaller islands. Only the three main islands were analysed during this study. Grande-Terre and Marie-Galante are characterized by a gently undulating surface where the local relief rarely exceeds 40 m. The northern and eastern parts of Basse-Terre present elongated hills with convex slopes. Dominating western Basse-Terre is a mountain chain oriented north–west to south–east. The mountain crest stands at 600 m in the north and at 1500 m in the south (i.e. La Soufrière volcano). The land west of the crest slopes steeply towards the Caribbean Sea. Southern Basse-Terre includes extensive areas of inclined flat surfaces. There are two protected areas where agriculture and deforestation has been excluded since 1970: the tropical rainforest including a part of the mountain massif of Basse-Terre (330 km^2), and the coastal wetland forest (30 km^2) (Fig. 1).

During this study we defined five AERs characterized by very different pedoclimatic conditions (Fig. 1):

- AER 1: the soils are vertisols (FAO classification) developed on coral reef limestone, characterized by a high clay content (80%) dominated by smectite, and a high cation exchange capacity (>50 cmol kg^{-1}). Soil depth ranges from 0.6 m to 1.8 m and the pH from 7.0 to 8.4 (Sierra et al., 2002). SOC stocks for the 0–0.25 m layer vary from 60 Mg ha^{-1} to 75 Mg ha^{-1} (Table 1). The mean air temperature is 26.5 °C and the mean annual rainfall is 1100 mm yr^{-1}, with a rainy season from June to November and a dry season from December to May.
- AER 2: the soils are kaolinitic ferralsols developed on old volcanic ash deposits. These soils are rich in active aluminium and iron hydrous oxides and their pH ranges from 4.5 to 5.5, while their cation exchange capacity ranges from 10 cmol kg^{-1} to 20 cmol kg^{-1} (Sierra et al., 2010). SOC stocks vary from 50 Mg ha^{-1} to 65 Mg ha^{-1} (Table 1). The mean air temperature is 25.4 °C and the mean annual rainfall is 2300 mm yr^{-1}.
- AER 3: the soils are andosols developed on young ash deposits. They are highly porous and have high aluminium content. Soil pH ranges from 5.0 to 6.5 and cation exchange capacity from 30 cmol kg^{-1} to 50 cmol kg^{-1} (Clermont-Dauphin et al., 2004). SOC stocks vary from 90 Mg ha^{-1} to 105 Mg ha^{-1} (Table 1). The mean air temperature is 23.9 °C and the mean annual rainfall is 3800 mm yr^{-1}.
- AER 4: the soils are nitisols rich in halloysite developed on ash deposits. Soil pH ranges from 5.0 to 6.5, and cation exchange capacity from 15 cmol kg^{-1} to 35 cmol kg^{-1} (Raphael et al., 2012). SOC stocks vary from 40 Mg ha^{-1} to 55 Mg ha^{-1} (Table 1). The mean air temperature is 25.0 °C and the mean annual rainfall is 2200 mm yr^{-1}.
- AER 5: the soils are vertisols similar to those described for AER 1 but soil depth does not exceed 0.4 m. SOC stock is about 50 Mg ha^{-1} (Table 1). The mean air temperature is 26.6 °C and the mean annual rainfall is 900 mm yr^{-1}. Rainfall distribution is similar to that of AER 1.

2.2. Land use and farming practices

Information on land use was obtained from the survey performed in 2011 by the Board of Food, Agriculture and Forestry

Table 1
Land area and use in each agro-ecological region (AER) and initial SOC stock for each cropping system.

AER	Land area	Area for each land use				Main cropping systems[a]	Initial SOC[b]
		Sugarcane	Banana	Grassland	Crop diversification		
	ha	%					Mg C ha^{-1} (%)
1	20600	50	1	39	10	Sugarcane monoculture	73 (25)
						Sugarcane (5)-yam (2–4)	62 (14)
						Sugarcane (5)-vegetable crops (5)	69 (20)
						Sugarcane (5)-melon (5)	74 (13)
2	6200	56	7	22	15	Sugarcane monoculture	59 (20)
						Sugarcane (5)-yam (2–4)	64 (18)
						Sugarcane (5)-pineapple (6)	59 (16)
						Sugarcane (5)-vegetable crops (5)	52 (17)
						Banana monoculture	63 (26)
3	2000	0	48	14	38	Banana monoculture	91 (36)
						Vegetable crops monoculture	103 (37)
						Banana (5)-vegetable crops (5)	89 (33)
4	2100	17	45	13	25	Banana monoculture	43 (13)
						Vegetable crops monoculture	55 (11)
						Banana (5)-vegetable crops (5)	54 (14)
						Sugarcane monoculture[c]	nd
5	600	0	10	25	65	Orchard	47 (22)
						Vegetable crops monoculture[c]	nd
						Banana monoculture[c]	nd
Total	31500	45	9	32	14		

[a] Values in brackets indicate the number of years of each crop within the rotation.
[b] Corresponds to the average SOC stock at the beginning of the study. Values in brackets indicate the coefficient of variation in%.

of Guadeloupe (Agreste, 2011). Information on farming practices were obtained from the survey carried out in the present study. The results concerning organic amendments will be presented in Section 3.1.

Sugarcane is the dominant crop in Guadeloupe, mainly in AERs 1 and 2, where it is present as a monoculture or in rotation with tuber and vegetable crops (Table 1). When sugarcane is cultivated in rotation this is under a 5-year cycle. The growth season is 12 months and harvest is mechanic, where residues (tops and leaves) are shredded before being returned to the soil surface. After harvest a new cane is cultivated, which grows from the stubble left behind are harvesting (ratoon crop). For this reason, soil tillage is only applied for planting in the first year of the cycle (Table 2). The first year mineral fertilizer is applied at planting and then two months after harvest. Most sugar production is exported to European markets.

The second type of land use involves natural grasslands, which are devoted to livestock production for the local market. These occupy about one third of the agricultural land and are distributed throughout all the AERs (Table 1). Livestock production is extensive with animals grazing unimproved pastures with moderate nutritive value so that their performance is poor. This system is adopted by risk adverse farmers, in which case the rate of conversion from grassland to cropland is negligible. This land use was excluded from the present study because only few data on natural grasslands are present in the soil database.

Banana is mainly cultivated in southern Basse-Terre (south of AER 2 and AERs 3 and 4; Table 1), this being associated with the high rainfall in this area. The cropping system is extremely intensive and involves high levels of pesticide and fertilizer use (Table 2). Fertilizer is splitted in 8–12 applications during the growth season. Banana is mainly cultivated as a monoculture (Table 1); when it is cultivated in rotation with vegetable crops its cycle is 5 year. The growth season varies markedly between plants (9–12 months), and then the initially homogeneous plant population becomes heterogeneous after few years. This process has a central influence on harvest (each plant is harvested separately) and also on soil cover and temperature (Raphael et al., 2012). Harvest is manual and residues (leaves and stems) are cut and placed on the soil surface. During growth each plant (mother plant) produces suckers issued from a lateral shoot (daughter plant) which grows after the harvest of the mother plant. For this reason soil tillage is applied only for planting in the first year of the cycle (Table 2). Most of banana production is exported towards European markets.

The spatial distribution of crops for the local market varies as a function of crop requirements. Although the crops cultivated in AER 1 generally require high levels of global radiation, mainly near harvest time, crops in AERs 2,3 and 4 require or tolerate soil acidity. Thus melon and pineapple are only cultivated in AERs 1 and 2, respectively, while vegetable crops (tomato, cabbage, salad, eggplant, pepper) are mainly cultivated in AERs 3 and 4, and secondarily in AER 1. Tuber crops, mainly water yam, are cultivated in AERs 1 and 2. Tropical fruits, mainly citrus, are cultivated mainly in AER 5. The length of the growth season varies with the species; e.g. 3–4 months for vegetable crops and melon, 8–9 months for yam and 18 months for pineapple.

Most of diversification crops are cultivated in rotation with export crops, and their cycle within the rotation varies from 2 years for yam to 6 years for pineapple (Table 1). Vegetable crops are also cultivated as a monoculture mainly in AERs 3 and 4. Soil tillage is rather intensive in these cropping systems with at least 4 passages of tillage tools per year (Table 2). Yam is cultivated on ridges prepared mechanically. The passage of tillage tools in orchard is devoted to weed control. In most crops fertilizer is applied at relatively high rates, mainly in pineapple (Table 2), and splitted in 2–3 applications during the growth season. Except for yam, harvest is realised manually and residues (leaves and stems) are placed on the soil surface or buried at 0.1–0.2 m depth. Pineapple residues are shredded before being returned to the soil. Yam harvest is made mechanically and residues (leaves and stems) are partially buried during ridge removal. Most farmers apply fallow after harvesting annual crops.

2.3. Soil database and survey of farming practices

Changes in SOC stocks were assessed using the Soil Database of the Agricultural Engineering Office CaribAgro in Guadeloupe. This database contains about 6000 soil analyses performed since 1998 throughout all the AERs. The database also comprises information on farmers (age, agricultural training), farms (location, number and size of plots, altitude, soil type) and soil characteristics (pH, bulk density, SOC, organic N, C/N ratio, available P, cations and cation and anion exchangeable capacity). Analyses were performed for the 0–0.25 m soil layer. Soil samples have been collected by the same team since 1998 and analyses have always been performed by the same laboratory in France. In order to assess changes in SOC stocks, plots were selected from the database. Local experts were also involved in this selection in order to identify farmers keeping written records of their farming practices. Thus only plots meeting the following criteria were conserved for calibration and testing of the model: (i) at least two soil analyses performed since 1998, (ii) the time elapsing between the first and last soil analysis was $\geq$8 yr, (iii) farmers had to provide reliable

Table 2
Current farming practices for the crops analysed in this study.

Crop	Length of the cycle[a]	Number of machinery passages[b]	Fertilizer	Organic amendment			
				Amended plots[c]	Type	Rate	Frequency of application
	yr		kg ha^{-1} yr^{-1} (N/P/K)	%			
Sugarcane	5	3 the first year, nil the following years	150/70/200	76	Vinasse	30 m^3 ha^{-1}	Every 5 years
Banana	5	3 the first year, nil the following years	400/80/180	29	Compost	50 Mg ha^{-1}	Every 5 years
Yam	2–4	4–5 per year	120/60/150	34	Manure or Sewage sludge	50 Mg ha^{-1} 40 Mg ha^{-1}	Once the first year
Vegetables	5	4–6 per year	120/60/150	61	Compost	5 Mg ha^{-1}	Every year
Melon	5	4–5 per year	120/60/150	5	Manure	50 Mg ha^{-1}	Once the first year
Pineapple	6	4–6 the first year, 2–3 the following years	150/50/200	22	Manure	40 Mg ha^{-1}	Once the first year
Orchard	perennial	2–3 per year	70/40/110	60	Manure	5 Mg ha^{-1}	Every 2 years

information on crop rotations and practices for the period between the first and last soil analyses. According to these criteria, 253 plots including 827 SOC measurements were selected for calibration and testing of the model. The effect of the cropping system and the AER on the changes observed in SOC stocks were determined by ANOVA under a two-way design (AnaStats, 2014).

Data on farming practices were collected during a survey performed on a network of 382 farmers corresponding to 433 plots, including the 253 plots selected to determine SOC stocks. The survey was performed with a team of two surveyors specifically hired for the needs of the study. The questionnaire focused on practices that directly or indirectly affected the evolution of SOC stocks: crop rotation and yield, management of crop residues, application of organic and lime amendments and mineral fertilizers, and type of soil tillage.

In addition to the interview, we also determined the amount of crop residues left after harvest for most of crops analysed in this study (e.g. banana, sugarcane, melon, pineapple, water yam, tomato, eggplant). For this, we selected six plots for each crop from the selected population of plots. For each plot, we sampled 1 m^2 quadrats with three replicates selected at random. The dry matter content of the residues was determined in the laboratory after drying at 70 °C for 72 h.

2.4. Description of the MorGwanik model

MorGwanik is a model designed to simulate changes in SOC as a function of annual C inputs and outputs. This model is similar to that proposed by Saffih-Hdadi and Mary (2008). The main differences from that model are that MorGwanik is able to account for the effects of different crops and crop cycles on the rate of SOC mineralization (e.g. annual with short or long growth season, pluriannual, perennial), and that it has been calibrated for the specific soil-climate-crop conditions of the Caribbean region. The basic equations of MorGwanik are as follows:

$$\frac{dC_{soil}}{dt} = (C_{res} \times h_{res}) + (C_{ame} \times h_{ame}) - \left[C_{soil} \times (k_{AER} \times k_{crop})\right] \qquad (1)$$

where C_{soil} (Mg C ha^{-1}) is the SOC stock; C_{res} (Mg C ha^{-1}) is the annual C input from crop residues (aboveground and roots); C_{ame} (Mg C ha^{-1}) is the annual C input from organic amendments; h_{res} and h_{ame} (unitless) are the humification coefficients of crop residues and organic amendments, respectively; k_{AER} (yr^{-1}) is the mineralization rate constant of C_{soil} in each AER; k_{crop} (unitless) is the coefficient accounting for the effect of the cropping system on k_{AER}. Under Eq. (1) the model assumes that crop residues and organic amendments are either decomposed or humified in the soil within the year of application.

The stock of SOC was calculated as:

$$C_{soil} = C_{soil-cont} \times (BD \times L \times 10000) \qquad (2)$$

where $C_{soil\text{-}cont}$ (Mg C Mg^{-1} soil) is the SOC content; BD (Mg soil m^{-3} soil) is the bulk density of the soil; L (m) is the depth of the soil layer analysed for C_{soil} (i.e. 0.25 m in this study) and 10,000 (m^2 ha^{-1}) is used to express C_{soil} by hectare. Carbon inputs from crop residues and organic amendments were calculated as:

$$C_{res} = Q_{res} \times C_{res-cont} \qquad (3)$$

$$Q_{res} = f(Y_{crop}) \qquad (4)$$

$$C_{ame} = Q_{ame} \times C_{ame-cont} \qquad (5)$$

where $C_{res\text{-}cont}$ and $C_{ame\text{-}cont}$ (Mg C Mg^{-1}) are the C contents of crop residues and organic amendments, respectively; Q_{res} (Mg ha^{-1}) is the total mass of aboveground crop residues; Y_{crop} (Mg ha^{-1}) is the crop yield; $f(Y_{crop})$ (Mg ha^{-1}) is the function used to convert crop yield into aboveground crop residues; and Q_{ame} (Mg ha^{-1}) is the rate of application of the organic amendment. While Q_{res} (Eqs. (3) and (4)) and Q_{ame} (Eq. (5)) are expressed as dry matter, Y_{crop} (Eq. (4)) is expressed as fresh matter.

The contribution of roots in the 0.25 m soil layer to crop residues was associated with some uncertainties because this input is not available for several tropical crops. We set root contribution as a fraction of the aboveground residues using data obtained from tropical regions for sugarcane (e.g. 16% of the aboveground residues; Chopart et al., 2010), tomato (13%; Ozier-Lafontaine and Bajazet, 2005), banana (18%; Raphael et al., 2012), and water yam (11%; Marcos et al., 2011). For other crops where data of root biomass was lacking (e.g. cabbage, salad, eggplant, pepper, pineapple and melon), the contribution of roots was set to the value used for tomato.

During this study, $C_{soil\text{-}cont}$ values were obtained from the soil database, and k_{AER} and k_{crop} were obtained from calibration of the model using the plots selected from the soil database. The humification coefficients h_{res} and h_{ame} were those reported by previous studies carried out in Guadeloupe (Table 3). Y_{crop} and Q_{ame} were obtained from the survey of farming practices. Q_{res} and $f(Y_{crop})$ were obtained from the sampling of crop residues in a part of the selected plots. $C_{res\text{-}cont}$ and $C_{ame\text{-}cont}$ were determined by the same laboratory as that used for soil analyses. Values for BD (Eq. (2)) were obtained from the soil database and averaged for

Table 3
Coefficients of humification for crop residues and organic amendments, and amount of aboveground crop residues at harvest.

	Humification coefficient	Reference	Aboveground crop residues Mg ha^{-1}
Crop residue			
Sugarcane	0.29	Sierra (2014)	Eq. (8)[a]
Banana	0.34	Raphael et al. (2012)	Eq. (9)[a]
Eggplant	0.33	Sierra (2014)	10.8
Melon	0.36	Sierra (2014)	4.3
Pineapple	0.31	Sierra (2014)	6.5
Tomato	0.37	Sierra (2014)	2.0
Yam	0.34	Ripoche et al. (2008)	6.2
Organic amendment			
Manure	0.51	Brisson et al. (2003)	
Vinasse	0.34	Brisson et al. (2003)	
Compost	0.58	Sierra (2014)	
Sewage sludge	0.45	Sierra (2014)	

[a] Aboveground crop residues for sugarcane and banana were expressed as a function of crop yield using Eqs. (8) and (9), respectively.

each soil type. The values of BD were set at 1.1 Mg m^{-3} for the vertisols of AERs 1 and 5, 1.0 Mg m^{-3} for the ferralsols of AER 2, 0.8 Mg m^{-3} for the andosols of AER 3, and 0.9 Mg m^{-3} for the nitisols of AER 4. Preliminary analysis of the soil database showed no evidence of any change in BD from 1998 for the soils of the selected plots. Therefore we assumed that BD values for each AER were constant over time. This assumption is discussed in Section 3.3.

MorGwanik was implemented for application in MS Excel$^{\text{TM}}$, and run on an annual time step by considering the crop rotation of each selected plot.

2.5. Calibration and testing of MorGwanik

The model was calibrated for k_{AER} and k_{crop} (Eq. (1)). For each cropping system – AER situation, 60% of the selected plots were used for model calibration (159 plots) and 40% to test the model (94 plots) (Table 4). The plots selected for model calibration and testing were distributed at random. When the number of selected plots for a given cropping system – AER situation was <20 (i.e. banana in AER 4 and orchard in AER 5; Table 4), all the plots were used for model calibration. The calibration and the test of the model were performed using the soil database (i.e. data on soil type and C_{soil}), data from the survey of farming practices (i.e. crop rotation and yield, management of crop residues and organic amendments) and the model parameters of C inputs from crop residues and organic amendments presented in Table 3. The k_{AER} and k_{crop} values estimated during the calibration phase were used for testing the model. In this way, the test of the model was conducted without fitting any parameter.

Calibration was performed in two phases, one involving five steps and the other four (Table 4). This was designed to minimize the number of parameters to fit in each step. Phase 1 (e.g. steps 1–5) was devoted to the banana and sugarcane monocultures and perennial orchards, the aim being to estimate k_{AER} for the five AERs and k_{crop} for banana, sugarcane and orchard. Phase 2 (i.e. steps 6–9) focused on the remaining cropping systems (i.e. diversification crops as a monoculture or in rotation with export crops) and the aim was to estimate k_{crop} for the diversification crops, using the k_{AER} values estimated during the first phase. When diversification crops were in rotation with banana or sugarcane, k_{crop} values for the latter were those estimated in steps 1 and 2, respectively. Similarly, the k_{crop} of banana and sugarcane obtained in steps 1 and 2 were used in steps 3 and 4 to estimate k_{AER} of AERs 2 and 4 (Table 4).

To reduce an eventual confounding effect between k_{AER} and k_{crop} during calibration, the fit of k_{AER} was performed under the condition $(k_{\text{AER-init}} \times 0.9) \leq k_{\text{AER}} \leq (k_{\text{AER-init}} \times 1.1)$, where $k_{\text{AER-init}}$ is the initial value of k_{AER} which was estimated from previous studies carried out in Guadeloupe at the plot scale. For this, the original data of N mineralization obtained by Sierra et al. (2002) in AER 1, by Sierra et al. (2010) in AER 2, and by Raphael et al. (2012) in AER 4, were reanalysed to express the rate of mineralization as an annual fraction of the SOC stock (Eq. (1)). Similarly, the diachronic measurements of SOC stocks carried out by Clermont-Dauphin et al. (2004) for several bare plots of AERs 3 and 5 were used to assess $k_{\text{AER-init}}$ in these AERs. The $k_{\text{AER-init}}$ values were 3.2×10^{-2} yr^{-1} for AER 1, 5.0×10^{-2} yr^{-1} for AER 2, 2.7×10^{-2} yr^{-1} for AER 3, 4.8×10^{-2} yr^{-1} for AER 4, and 2.7×10^{-2} yr^{-1} for AER 5.

For each step, calibration was performed simultaneously for all the selected plots of the cropping system—AER situation. The criterion that was minimised was the absolute root mean square error (RMSE) calculated as:

$$\text{RMSE} = \left[\frac{\left(\Sigma(\text{obs}C_{\text{soil}} - \text{pre}C_{\text{soil}})^2\right)}{n}\right]^{0.5} \tag{6}$$

where obs C_{soil} (Mg ha^{-1}) is the observed value of the SOC stock obtained from the soil database; pre C_{soil} (Mg ha^{-1}) is the SOC stock predicted by the model, and n is the number of observations for each cropping system—AER situation (Table 4). The fit was conducted using the Newton's method of the MS Excel$^{\text{TM}}$ solver. We also calculated the relative root mean square error (RRMSE in%) to complete the description of calibration quality:

$$\text{RRMSE} = \frac{\text{RMSE}}{\text{obs}_{\text{mean}}C_{\text{soil}}} \tag{7}$$

where obs$_{\text{mean}}$ C_{soil} is the mean value of obs C_{soil} for each step. RMSE and RRMSE were also calculated to assess the quality of testing.

2.6. Model simulations

The calibrated and tested model was used to simulate the effects of partially replacing food imports by converting 50% of the area occupied by sugarcane monocultures in AERs 1 and 2 into a rotation of sugarcane for 5 yr followed by vegetable crops for 5 yr.

Table 4
Results obtained for the nine steps of calibration and testing of the model.

Step	AER[a]	Cropping system	Calibration of the model							Testing of the model				
			Plots	Obs. (b)	R^2	RMSE Mg ha^{-1}	RRMSE %	k_{AER} yr^{-1}	k_{crop}	Plots	Obs. (b)	R^2	RMSE Mg ha^{-1}	RRMSE %
1	3	Banana (M[c])	22	62	0.92	7.2	9.7	0.026	0.57	15	45	0.90	9.8	11.6
2	1	Sugarcane (M)	15	55	0.76	7.1	9.7	0.034	0.85	11	42	0.86	7.8	10.3
3	2	Banana and sugarcane (M)	19	69	0.75	5.8	10.4	0.046	(e)	14	54	0.80	6.5	9.6
4	4	Banana (M)	11	35	0.72	4.1	9.5	0.046	(e)	nd	nd	nd	nd	nd
5	5	Orchard	10	28	0.92	2.1	4.0	0.025	0.22	nd	nd	nd	nd	nd
6	1, 2, 3, 4v	Vegetable crops (M and R[c])	26	65	0.90	7.8	10.8	(d)	1.19	17	45	0.92	6.4	9.8
7	2	Pineapple (R)	29	110	0.56	4.5	8.3	(d)	0.95	20	76	0.64	4.6	8.4
8	1, 2	Yam (R)	15	60	0.81	4.3	7.0	(d)	1.26	9	29	0.91	3.7	6.0
9	1	Melon (R)	12	31	0.74	4.4	6.5	(d)	0.92	8	21	0.63	3.7	5.3
Total			159	515						94	312			

nd, not determined. All plots were used for calibration of the model when the total number of plots was <20.

[a] Agro-environmental region.

[b] Number of SOC measurements.

[c] M: monoculture; R: rotation with banana or sugarcane (see Table 1 for the characteristics of each rotation).

[d] k_{AER} values used in steps 6–9 were those estimated in steps 1–5.

[e] k_{crop} values used in steps 3 and 4 were those estimated in steps 1 and 2.

The initial SOC stock was set at the equilibrium value under sugarcane monoculture; i.e. 2.5% SOC or 70 Mg C ha^{-1} for AER 1 and 1.8% SOC or 47.6 Mg C ha^{-1} for AER 2. Sugarcane yields were set at 65 Mg ha^{-1} in AER 1 and 55 Mg ha^{-1} in AER 2, which correspond to the mean values obtained for each AER from the survey of farming practices. It was assumed that the aim of the farmers was to maintain the initial level of SOC (i.e. the equilibrium value under sugarcane monoculture). We tested the impact of two practices currently proposed in the Caribbean to enhance the sustainability of agriculture devoted to local markets (IFAD, 2014): the use of compost to increase C inputs, and reduced soil tillage to decrease C outputs. Both practices were applied to the rotation period occupied by vegetable crops.

An additional simulation was performed to analyse the effect of an increase in sugarcane yield in AER 2 (i.e. the effect of an increase in the amount of crop residues). We considered that such yield increases might be obtained by applying liming to the acid ferralsols of AER 2. Sugarcane yields in this simulation were therefore set at the mean value obtained from the survey for sugarcane plots limed within the past 5 yr in AER 2 (e.g. 64 Mg ha^{-1}). The model parameter values used for all the simulations were those detailed in Tables 3 and 4 for compost, sugarcane and vegetable crops.

3. Results and Discussion

3.1. Carbon inputs from organic amendments and crop residues

The results indicated that 41% of the plots surveyed received at least one application of organic amendment within the rotation cycle. For a given cropping system, the frequency and the rate of application differed little between AERs. On the contrary, they varied markedly between cropping systems (Table 2). Sugarcane and banana only received organic amendments when they were as a monoculture. When these crops were in rotation, only the diversification crops were amended. Although sugarcane monoculture was the system with the higher proportion of amended plots, the rate of C input was low because vinasse derived from the sugarcane industry was the only amendment applied under this system. In fact, vinasse is characterised by a low C content (e.g. 6.5 g C L^{-1}; Panon et al., 2001), and then the current rate of 30 m^3 ha^{-1} (Table 2) corresponds to only 0.2 Mg C ha^{-1}. Vinasse is used mainly to add available K to the crop (e.g. 200 kg K ha^{-1} at the current rate). It is interesting to point out that for the rate of vinasse currently used in Guadeloupe, the amount of heavy metals applied to the soil is much below the mandatory standards established by the French regulation (Panon et al., 2001).

Expressed in terms of humified C input, the rates of organic amendments varied from 0.1 Mg humified C ha^{-1} for sugarcane monoculture to 3.6 Mg humified C ha^{-1} for banana monoculture. In terms of annual humified C input, the highest values corresponded to banana and vegetable crops (i.e. about 0.4 Mg humified C ha^{-1} yr^{-1}). As it will be discussed later, these values of C input from organic amendments are too low to off set C losses from SOC mineralisation for most cropping systems. This management of organic inputs might be due to the fact that farmers tend to use organic amendments as a source of available nutrients for crops rather than as a source of organic matter for soils. As reported by Hernández et al. (2014), the use of organic amendments to replace or reduce inorganic fertilization needs organic products with a low rate of humification in soils. In fact, Sierra (2014) reported that the humification coefficient for N was 0.96 for the compost and 0.25 for the sewage sludge used in Guadeloupe. This implies that while sewage sludge could provide a suitable amount of available

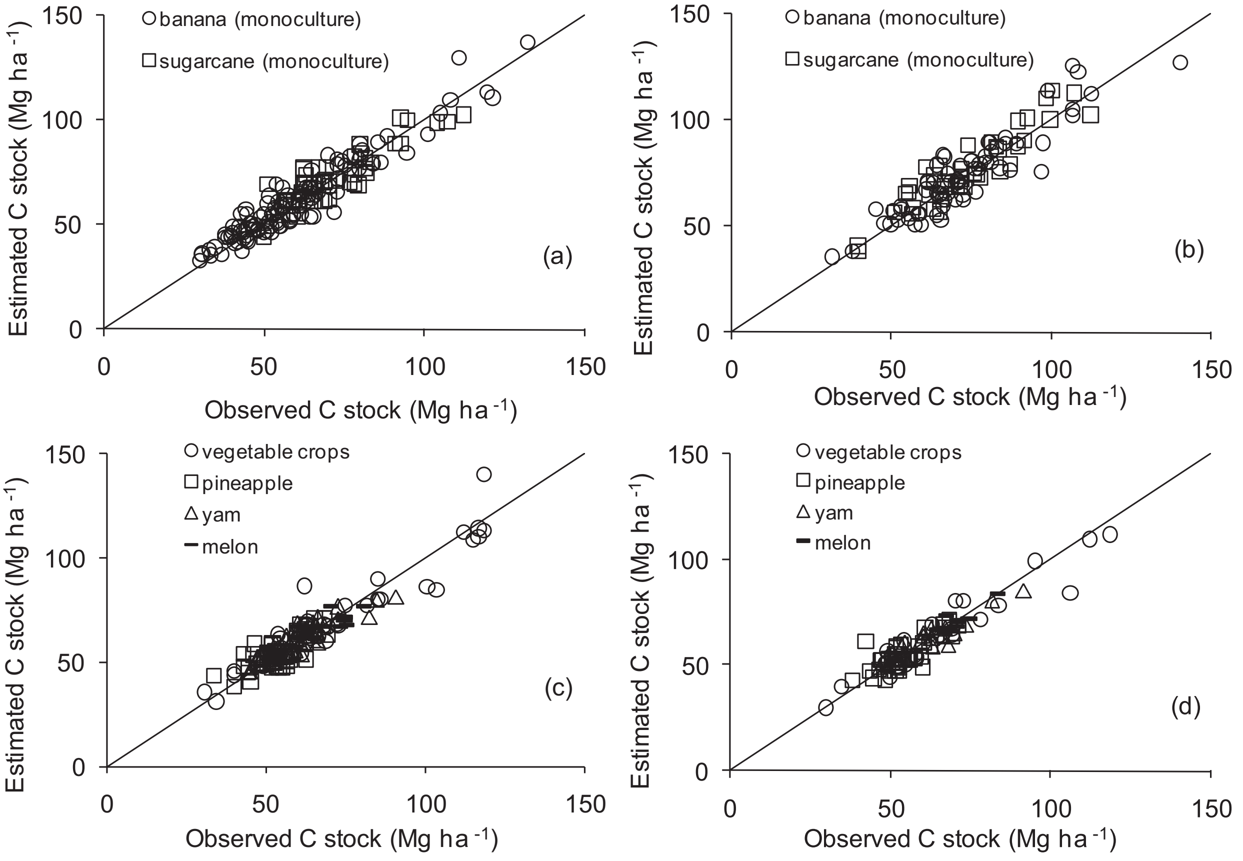

Fig. 2. Relationship between observed and predicted soil organic C stocks: (a), (c) calibration and (b), (d) testing of the model. The lines indicate the 1:1 relationship.

N, most of the N in the compost will be sequestered in soil organic matter. Therefore, only a few organic amendments might play a major role in Guadeloupe in providing available nutrients for crops in the short term. This is the case of vinasse for K and sewage sludge for N.

Expressed as dry matter, average aboveground crop residues ranged from 2 Mg $ha^{-1} yr^{-1}$ for vegetable crops such as tomato to 15 Mg $ha^{-1} yr^{-1}$ for sugarcane (Table 3). In terms of C inputs, the values ranged from 0.3 Mg humified C $ha^{-1} yr^{-1}$ for tomato to 1.9 Mg humified C $ha^{-1} yr^{-1}$ for sugarcane. Only a few farmers reported the removal of residues after harvest, because of attacks by fungal diseases during the crop cycle (Ripoche et al., 2008). In these cases, the residues were burned out of the plot. This mainly concerned vegetable crops and yam. For crops with relatively large quantities of residues (e.g. sugarcane, banana), the annual C input from residues was higher than that resulting from organic amendments. The contrary was the case for crops such as yam and tomato, with small quantities of crop residues. However, as only a fraction of the plots in each cropping system received organic amendments, crop residues represented the principal C input when considering each overall cropping system. Lal (2008) also reported that the amount of residues from pluriannual crops was 3–8 times higher than that from annual crops. In the present study, differences between crops regarding the amounts of residues (coefficient of variation (CV): 57%) were much higher than those observed for the humification coefficient (CV 8%; Table 3). This implies that the differences between cropping systems regarding C inputs from residues were primarily controlled by the amount of residues and only secondarily by their quality.

The results of the survey indicated that while most farmers provided yield data for sugarcane and banana (84%), only a few cultivators were able to provide reliable yield data for diversification crops (2%). This is also the situation in other countries of the Caribbean region (FAO Subregional Office for the Caribbean, 2013). Indeed, more data is available on yields of export crops because it is recorded by the exporting company or the sugar factory. By contrast, vegetable and tuber crops devoted to the local market are distributed outside commercial networks (Barlagne, 2014). Therefore, in the present study the relationship between yields and crop residues (Eq. (4)) could only be established for the sugarcane and banana. For sugarcane, the relationship was:

$$Q_{res-sugarcane} = 8.2 + 0.11 \times Y_{sugarcane} \quad R^2 = 0.76 \tag{8}$$

for banana:

$$Q_{res-banana} = 0.5 + 0.22 \times Y_{banana} \quad R^2 = 0.81 \tag{9}$$

For modelling purposes, when yield data for sugarcane and banana were not available, they were set at the mean values obtained from the survey of farming practices; i.e. for sugarcane: 65 Mg ha^{-1} in AER 1 and 55 Mg ha^{-1} in AER 2; for banana: 30 Mg ha^{-1} in AER 2, 35 Mg ha^{-1} in AER 3 and 32 Mg ha^{-1} in AER 4. For other crops, Q_{res} was set at the mean value obtained from the sampling of crop residues carried out in the selected plots (Table 3). For vegetable crops with low levels of residues, such as salad and cabbage, we used the value obtained for tomato. For vegetable crops with high levels of residues such as pepper, we used the value obtained for eggplant.

3.2. Carbon outputs: calibration and testing of the model

The results of calibration and testing of the model are presented in Table 4 and Fig. 2. The model was able to provide satisfactory estimates of changes in SOC stocks. The R^2 was >0.70 ($P < 0.05$), except for pineapple in rotation with sugarcane (step 7 in Table 4). RMSE and RRMSE values averaged 5.2 Mg C ha^{-1} and 8.5%, respectively. These values were slightly higher than those reported in other studies on the modelling of the changes to SOC stocks performed at the plot scale (e.g. Saffih-Hdadi and Mary, 2008), but were similar to values found in studies carried out at the regional scale (e.g. Cerri et al., 2007). Indeed, the higher spatial variability found at the regional scale affects model performances when a single set of parameters is used to describe SOC changes for the overall region (Cerri et al., 2007). The reason for the lower fit quality observed for pineapple in AER 2 was not clear because the impact of other cropping systems in the same AER was correctly described by the model; e.g. banana and sugarcane in step 3 and yam in step 8. This suggests that management of the pineapple cropping system might be the major factor affecting model calibration. For example, about one third of pineapple plots were mulched with plastic films, which could increase k_{crop} by increasing SOC mineralization because of the effect of mulch on soil temperature and moisture (Zhang et al., 2012). Taking into account that calibration was performed simultaneously for all the selected plots of each cropping system—AER situation, such an effect of mulching could increase the spatial variability of model parameters at the regional scale and then affect model performance.

The statistical parameters obtained from testing the model were similar to those found for calibration. Moreover, in some cases the quality of model fit was better during testing; e.g. steps 2, 3 and 8. Taking account of the fact that calibration and testing of the model were performed using independent sub-populations of plots, the results of testing confirmed that the model was suitable to quantify changes in SOC stocks. The estimated k_{AER} values well reflected the soil and climatic conditions of each AER (Table 4). The highest values were found for AERs 2 and 4, characterized by a warm and humid climate and soils containing low activity clay with relatively low SOC retention (Cabidoche et al., 2004). Despite the similar k_{AER} values in these regions, absolute C mineralization for a given C content and type of soil management could be expected to be greater for AER 2 because its higher soil bulk density and SOC stocks (Table 1). The lowest k_{AER} was observed in AER 5, which experiences a marked dry season from December to May that partially limits SOC mineralization (Cabidoche and Ozier-Lafontaine, 1995). The dry season is less severe in AER 1 which explains why k_{AER} was higher in this region than in AER 5 (Sierra et al., 2002). Moreover, the vertisols of AER 1 and 5 are characterized by high activity clay which contributes to retaining SOC (Cabidoche and Ozier-Lafontaine, 1995). The low k_{AER} found in AER 3 may have been associated with the presence of amorphous allophane clay with a very high capacity for SOC sequestration (Cabidoche et al., 2009) and, as discussed above, to a relatively lower temperature. Most models for SOC dynamics consider that the mineralization rate is affected by the soil clay content (e.g. Parton et al., 1987; Brisson et al., 2003). This approach is probably irrelevant in the Caribbean because most soils have very high clay content (e.g. 70–80%; Cabidoche et al., 2004). Wattel-Koekkoek et al. (2003) found that clay mineralogy was the principal factor affecting the mean residence time of SOC in soils rich in kaolinite and smectite. This was undoubtedly the case in the present study where the differences between the soils of different AERs in terms of their clay mineralogy were greater than for their clay content. Further work is necessary to develop a more mechanistic approach to estimating k_{AER} as a function of clay mineralogy so as to be able to assess SOC dynamics in transitional soils, which are common in the Caribbean.

The estimated k_{crop} varied mainly according to the length of the crop and the rotation cycle which determines the intensity of soil tillage; e.g. the longer the planting-to-planting period, the lower the intensity of soil tillage for the entire rotation cycle. For example, the lowest value was observed for perennial orchard, followed by pluriannual crops such as banana and sugarcane (cycle 5 yr), where soil tillage is only applied at the beginning of each cycle (Table 2). As described above, the lower banana k_{crop} value when compared to sugarcane could be ascribed to greater soil cover over time, lowering the soil temperature and then SOC mineralization (Raphael et al., 2012; Sierra et al., 2010). The highest k_{crop} values were found for vegetable crops and yam. The survey of farming practices indicated that these cropping systems included intensive soil preparation in order to establish ridges with highly uniform soil conditions (Table 2), which accelerates SOC decomposition (Bajgai et al., 2015). Moreover, further soil disturbance occurred at the time of harvest for tuber crops such as yam when ridges are removed mechanically. Intermediate k_{crop} values were found for pineapple and melon. In the former case, it is possible that the impact of intensive tillage performed before planting was diluted by a 3–6 yr cycle. For melon, the fallow following harvest is occupied by herbaceous plants that are turned and incorporated into the soil before the following melon planting, which may contribute to increasing C inputs.

With the k_{AER} and k_{crop} values obtained in this study, and using the initial SOC stock detailed in Table 1, it may be calculated that C outputs from mineralization at the beginning of the analysed period varied from 0.3 Mg C ha^{-1} yr^{-1} for orchard in AER 5–3.7 Mg C ha^{-1} yr^{-1} for yam in AER 2, with an average value of 2.3 Mg C ha^{-1} yr^{-1} considering all the cropping system—AER situations. This average value is 6 times higher that the maximum input of humified C from organic amendments estimated in this study (i.e. 0.4 Mg ha^{-1} yr^{-1}). This indicates that organic amendments could not compensate C outputs from mineralization in most cropping systems, which was mainly due to the low rate and frequency of these inputs. From these results, it appears that

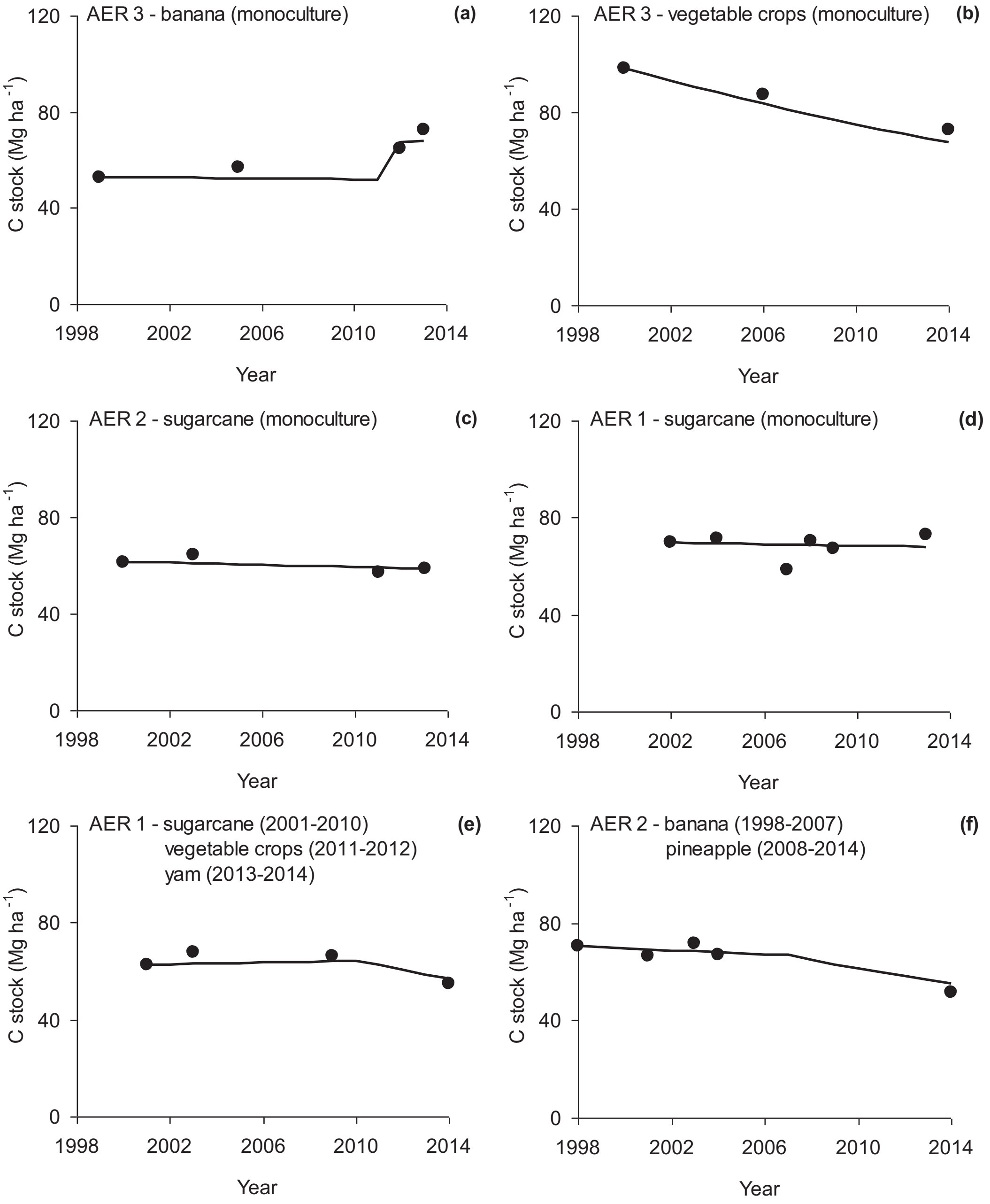

Fig. 3. Changes in SOC stocks in six contrasted cropping system – agro-ecological region (AER) situations observed in this study. ● observed and — predicted SOC stocks.

perennial and pluriannual crops (sugarcane, banana and orchard), with higher C inputs from crop residues or lower C outputs than annual crops, would be more able to preserve SOC stocks under the Caribbean conditions.

3.3. Relationship between the observed changes in SOC stocks and model parameters

It is well known that tillage and cropping system are major factors affecting soil structure and bulk density (e.g. Villamil et al., 2015). Indeed changes in bulk density over time may affect the mineralization rate by affecting soil aeration as well as the calculations of SOC stocks (Eq. (2)). As cited above, preliminary analysis of the soil database indicated that bulk density was rather stable in the soils of the plots selected for the present study, and then we assumed no temporal changes in that variable. This assumption agrees with the results reported by Dörner et al. (2012) for soils derived from volcanic ash similar to those of AERs 2–4, and by Ozier-Lafontaine and Cabidoche (1995) for vertisols of AERs 1 and 5. Dörner et al. (2012) found that volcanic soils present a high resilience capacity, which allows a fast recuperation of the functionality of soil structure after mechanical disturbance. Similarly, fast pore space redistribution associated to the swelling-shrinkage processes in vertisols ensures resilience of soil structure in these soils in the medium term (e.g. a few months after tillage; Ozier-Lafontaine and Cabidoche, 1995). From this, we concluded that no change in bulk density was a reasonable assumption in the present study.

Fig. 3 shows the changes in SOC stocks for some cropping system—AER situations observed during the present study, such as:

- banana in AER 3 (Fig. 3a): in this plot, banana was cultivated for about 20 yr as a monoculture which induced a quasi-equilibrium of SOC stocks. The abrupt rise seen in 2012 was due to an application of compost at a rate as high as 200 Mg ha^{-1}.
- vegetable crops in AER 3 (Fig. 3b): the plot had been cultivated with vegetable crops (e.g. salad, tomato, pepper, eggplant) for the past 14 yr. No organic amendment was applied to this plot. The SOC stock fell by 31% between 2000 and 2014, corresponding to a rate of −2.2 Mg C ha^{-1} yr^{-1}. This indicates that SOC losses may be very important under vegetable crop systems, even in soils rich in allophane with a high capacity for SOC sequestration.
- sugarcane in AERs 1 and 2 (Fig. 3c and d): most of the sugarcane crops in these AERs had been cultivated as monocultures during the past three decades, which determined a quasi-equilibrium of SOC stocks. Quasi-equilibrium of SOC in the tropics had also been reported by Bhattacharyya et al. (2007) for soils of the Indo-Gangetic Plains under rice-wheat cropping systems for 30–40 yr.
- vegetable crops-yam in AER 1 (Fig. 3e) and pineapple in AER 2 (Fig. 3f) in rotation with sugarcane: the quasi-equilibrium obtained under sugarcane monoculture could rapidly be disrupted by introducing crop diversification. For example, SOC stocks fell by 11% after 4 yr of vegetable crops and yam

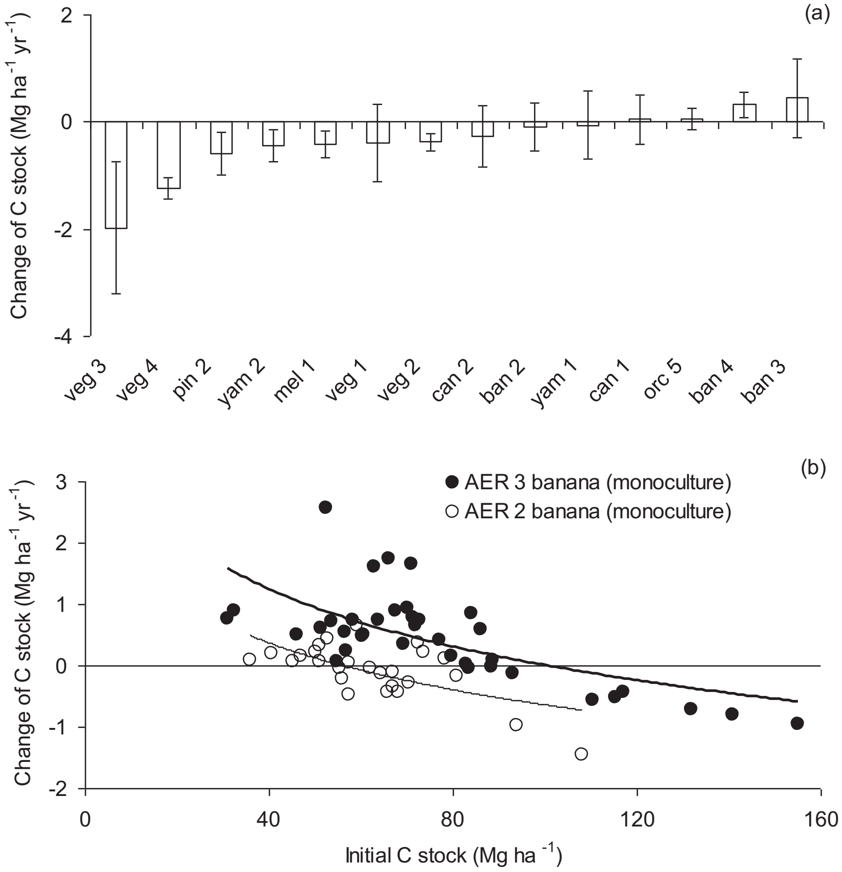

Fig. 4. (a) Changes in SOC stocks for the 14 cropping system – agro-ecological region (AER) situations assessed during this study. Vertical bars indicate the standard deviation (see Table 3 for the number of observations). veg: vegetable crops; pin: pineapple; yam: water yam; mel: melon; can: sugarcane; ban: banana and orc: orchard. The numbers after the crop code indicate the agro-ecological region as detailed in Fig. 1(b) Changes SOC stocks as a function of the initial stock for banana monocultures in AERs 2 and 3. See Fig. 1 for the description of each AER.

(Fig. 3e), and by 15% after 6 yr of pineapple (Fig. 3f). No organic amendments were applied to these plots.

The overall results regarding the changes observed in SOC stocks are presented in Fig. 4a. Taking account of the fact that the rotation length varied between the selected plots, the results were expressed on an annual basis. The largest drop in C stocks concerned vegetable and tuber crops as expected since their C outputs (k_{crop}) were higher and C inputs were generally smaller than those of export crops. In terms of the initial C stock, C losses for these crops ranged from −1.6% yr^{-1} for vegetable crops in AER 3 to −0.1% yr^{-1} for yam in AER 1. These values were similar to those reported by Bhattacharyya et al. (2007) for double- or triple-cropping systems (i.e. two or three crops grown in a year), including vegetables, in the Indo-Gangetic Plains. These authors concluded that the introduction of double- or triple-cropping systems without adequate nutrient and organic matter management could exhaust the soil. In the present study, while triple-cropping systems were not detected in the survey, about 20% of the plots cultivated with vegetable crops presented double-cropping systems. As discussed above, the results obtained for vegetable and tuber crops suggest that *C* outputs from SOC mineralization were not offset by *C* inputs from organic amendments because of the relatively low rates of application considering the entire rotation cycle. The variation of the changes of SOC stocks for each cropping system was very high and CV values averaged 400% (Fig. 4a). Such variation was linked to three factors: (i) changes in the management of organic amendments (i.e. with and without amendments, changes in the rates of application), (ii) changes in the proportion of different crops within the rotation (i.e. change in the amount of crop residues throughout the rotation cycle and in k_{crop} over time), and (iii) changes in the initial *C* stock (i.e. the higher the initial *C* stock, the higher the *C* loss; Fig. 4b). In Fig. 4b, the higher SOC loss in AER 2 for a given initial C stock reflected its higher k_{AER}.

Ogle et al. (2005) reported that the decline of SOC stocks in soils under agriculture was higher in moist than in dry tropics, but the authors concluded that it was not possible to determine the reasons for such climatic patterns because of the many and complex interactions between *C* inputs and outputs under each climate. In the present study, the behaviour of vegetable crops, sugarcane and yam (Fig. 4a) were in line with the proposal of these authors, even though the underlying reasons differed for each cropping system. For vegetable crops, the higher *C* loss observed in the more humid AER 3 by comparison with AER 1 was mainly due to its very high initial *C* stock (Table 1). For sugar cane, the differences between AERs 1 and 2 were principally linked to differences in crop yields and then in the amount of residues incorporated into the soil; e.g. mean yield 55 Mg ha^{-1} in AER 2 and 65 Mg ha^{-1} in AER 1. The reduction in sugarcane yields in AER 2 would be due to the increased soil acidity of ferralsols because of the reduction in the frequency of liming in this region (Gardel Sugar Factory, comm. pers.). This was confirmed by our survey because only 5% of sugarcane farmers in AER 2 had applied lime amendments during the past 10 yr. Also, the SOC loss for yam systems was 7-fold less in AER 1 than in the more humid AER 2, which was mainly associated with the lower k_{AER} in this region (Table 4).

In contrast with the proposal of Ogle et al. (2005),Fig. 4a shows that only banana monoculture systems in the more humid AERs 3 (+0.9% yr^{-1}) and 4 (+0.8% yr^{-1}) presented a clear sequestration pattern, while this system presented a slight decline in SOC stocks in AER 2. Carbon sequestration in banana systems in AERs 3 and 4 was due to their relatively low C outputs (i.e. low k_{crop}) together with relatively high *C* inputs from crop residues and organic amendments (e.g. Table 2 and Fig. 3a). The level of *C* sequestration in these banana systems was within the range of values reported by several authors for humid tropics (Lal, 2004; Cerri et al., 2007).

Table 5
Analysis of variance of the observed changes in SOC stocks.

Source of variation	Contribution to total variance%	*F*	Level of significance
AER[a]	5	68	<0.001
Cropping system	64	630	<0.001
AER × cropping system	26	256	<0.001
Error	5		

[a] Agro-environmental region.

ANOVA indicated that the cropping system, the AER and their interaction significantly affected the SOC stocks observed in this study (Table 5). However, the cropping system was by far the principal factor affecting SOC and accounted for about two–thirds of the total variance of the observed data. The stronger impact of the cropping system compared with the AER can be seen in Fig. 4a, where the highest *C* loss and highest *C* sequestration were observed for systems in the same region; i.e. vegetable crops and banana in AER 3, respectively. These results confirm that cropping systems can be managed to improve SOC stocks in the tropics despite the favourable climatic conditions for SOC mineralization.

3.4. Simulation of the diversification and import replacement scenario

The soils under the simulated rotation of sugarcane for 5 yr followed by vegetable crops for 5 yr lost about 6% of their initial SOC stocks by the end of the simulated rotation cycle, when organic amendments were not applied (Table 6). When sugarcane yields were set at the currently observed values (i.e. 65 Mg ha^{-1} for AER 1 and 55 Mg ha^{-1} for AER 2), the rate of compost application required to preserve the initial SOC stocks averaged 10 Mg ha^{-1} yr^{-1}. Considering the land area of AERs 1 and 2 involved in the simulation (e.g. 5100 ha in AER 1 and 1740 ha in AER 2), such a rate of application would correspond to a compost production of about 72,000 Mg yr^{-1}. This value is unrealistic under the current conditions prevailing in the Caribbean when considering that only a few composting platforms are actually available. For example, there is only one composting platform in Guadeloupe, which produces 21,000 Mg yr^{-1}. With this in mind, we tested the combined effect of compost application and reduced soil tillage to preserve SOC stocks on vegetable crops. Because no information is available on the effects of reduced tillage on SOC mineralization in Caribbean soils, we considered that this practice would decrease the estimated k_{crop} value obtained for vegetable crops (i.e. 1.19) to the level of that found for pineapple (i.e. 0.95). Applying this k_{crop} value, the amount of compost required to maintain the initial SOC stocks decreased by 65% in AER 1 and 81% in AER 2 (Table 6). At these rates, annual compost production would need to be about 23,000 Mg yr^{-1}, which is close to the current level in Guadeloupe. The importance of reduced soil tillage or no-till to preserving SOC stocks in the tropics has already been pointed out by several authors (e.g. Zinn et al., 2005; Huerta et al., 2014). For example, Huerta et al. (2014) reported that the use of organic amendments had a positive effect on SOC storage in tropical soils, but the impacts were mostly less than those achieved using reduced tillage. These authors concluded that reducing *C* outputs is more relevant than increasing *C* inputs to preserve SOC stock in tropics.

Increasing sugarcane yields may be another factor that could contribute to preserving SOC stocks. As discussed above, the increase in sugarcane yields in AER 2 could be achieved by liming to enhance soil pH. For example, if sugarcane yields in AER 2 increase to the levels of the limed plots observed in our survey (i.e. from 55 Mg ha^{-1} to 64 Mg ha^{-1}), crop residues would increase

Table 6
Simulation of the effects of the rotation of sugarcane for 5 yr followed by vegetable crops for 5 yr on SOC stocks.

AER[a]	Sugarcane yield	SOC loss[b]	Compost rate to achieve equilibrium[c]	
	Mg ha^{-1}	% of the initial stock	k_{crop} = 1.19[d] Mg ha^{-1} yr^{-1}	k_{crop} = 0.95[e]
1	65	−5.6	11.5	4.0
2	55	−6.2	7.8	1.5
2	64	−5.2	6.6	0.2

[a] Agro-ecological region.
[b] SOC loss at the end of the simulated rotation cycle without organic amendment or reduced tillage.
[c] Annual rate of compost application to vegetable crops required to maintain the initial C stocks (i.e. to avoid SOC losses).
[d] Corresponds to the value estimated for vegetable crops.
[e] Correspond to the value estimated for pineapple and used to simulate reduced soil tillage.

by 7% which would be sufficient to maintain the initial SOC stock by applying reduced tillage to vegetable crops and a relatively low rate of compost (Table 6). Although an accurate assessment of the effects of reduced tillage on k_{crop} needs further investigation, our calculations indicate that the negative impact of crop diversification on SOC stocks in the Caribbean may be offset by combining different farming practices, including organic amendments, reduced soil tillage and liming in acid soils.

4. Conclusions

The case study of Guadeloupe provides a good representation of the spatial heterogeneity of the Caribbean which is characterized by a mosaic of soils, climates, crops and farming practices. The changes observed in SOC stocks within each combination of cropping system – agro-ecological region were extremely variable and were driven primarily by the traits of the cropping system and secondarily by the soil – climate conditions of the region. This implies that cropping systems can be managed to maintain or improve SOC stocks in the tropics despite favourable climatic conditions for mineralization.

One key question that was raised during the analysis of this case study was the sustainability of export and diversified agriculture with respect to maintaining, increasing or decreasing SOC stocks. While sugarcane and banana monocultures were mostly able to preserve or increase SOC, diversification based on vegetable and tuber crops was likely to reduce SOC. Despite this, export crops, mainly banana, are major responsible for GHG emissions due to high N fertilizer inputs and for long-term pollution of soils by pesticides. In this context, agri-environmental schemes proposed to reduce the negative environmental impacts of export crops should include measures to preserve their positive effects on SOC storage.

The results of this study indicated that SOC losses under diversified cropping systems could be halted or mitigated by adopting reduced soil tillage, organic amendments and liming in more acid soils. These results suggest that a reorientation of the strategy of Caribbean agriculture towards replacing food imports needs to be accompanied by changes in farming practices, which will require the implementation of new agricultural policies at the farm and the regional scales.

Despite its simplicity, the MorGwanik model adequately simulated the evolution of SOC under export and diversified agriculture, and allowed us to assess the consequences of crop diversification and rotations, and define strategies at the AER scale. Further improvements of the model should concern the effects of changes in farming practices on k_{crop} (e.g. impact of reduced or no-till management) and the effect of clay mineralogy on k_{AER}. The latter is particularly important when applying the model in Caribbean regions with a high proportion of transitional soils.

Acknowledgements

This study formed part of the TropEmis Project funded by the Reacctif Programme of the French Agency for the Environment and Energy Management (ADEME), the European Regional Development Fund (FEDER) and the Regional Council of Guadeloupe. We are grateful to the Agricultural Engineering Office Carib Agro, which allowed us to use its soil database, and to the 382 farmers who were interviewed for this study. We would like to thank F. Solvar and J. Leinster for their excellent assistance during the study and V. Hawken for reviewing the English manuscript. We thank the anonymous reviewers for their constructive comments, which helped us to improve the manuscript.

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Annexe 6

Diaporama de présentation au programme Prospective 2040 Guadeloupe

Changement climatique & agriculture en Guadeloupe.
Synthèse des résultats
des projets Climator et TropEmis

Jorge Sierra
Unité AgroSystèmes Tropicaux – INRA Antilles-Guyane

INRA SCIENCE & IMPACT
AGENCE NATIONALE DE LA RECHERCHE ANR
ADEME Agence de l'Environnement et de la Maîtrise de l'Energie
REGION GUADELOUPE
l'Europe s'engage en Guadeloupe avec le FEDER

Avant de commencer : *les incertitudes !*

Sur le CC lui-même :

- comportement de la société humaine
- modélisation climatique
- cas Guadeloupe : petit territoire entouré d'eau

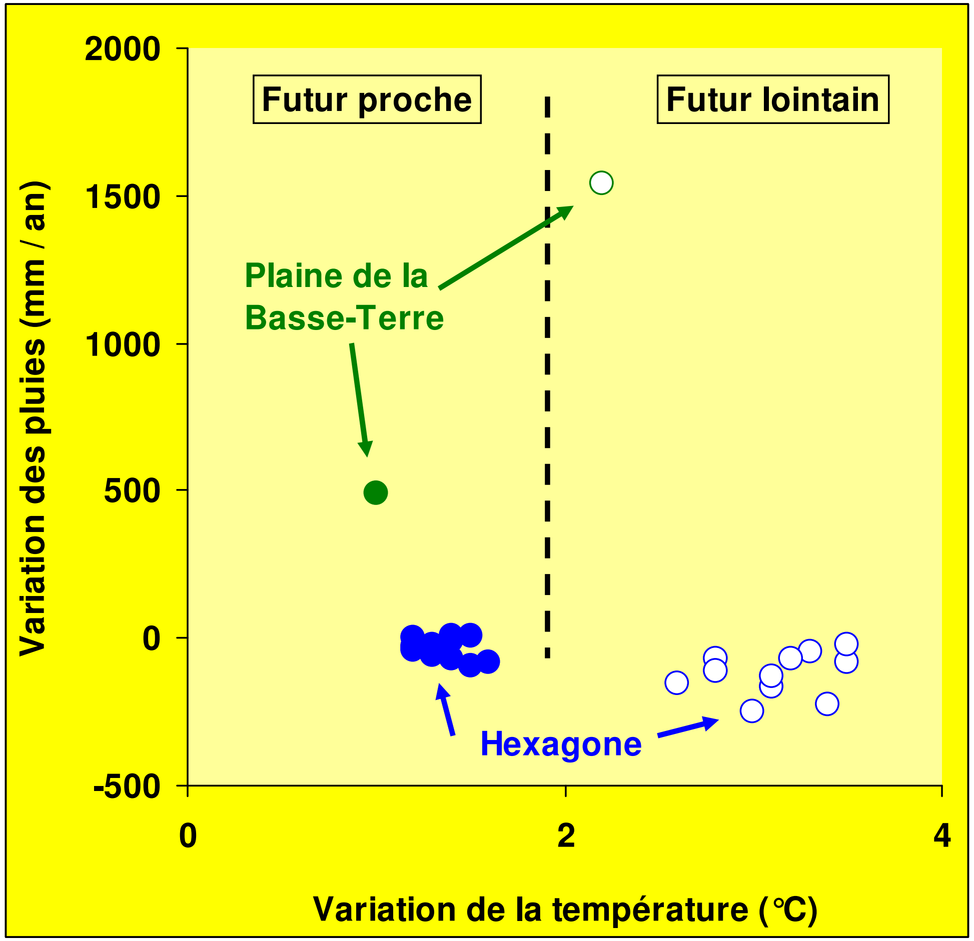
Sur le système à étudier :

- méconnaissance du fonctionnement (résistance, résilience, etc.)
- méconnaissance des seuils face au CC

A quoi faut-il s'adapter ?

INRA
SCIENCE & IMPACT

Le CC en Guadeloupe



Rayonnement global
–10% dans le FP
–20% dans le FL

Déplacer les températures à droite …

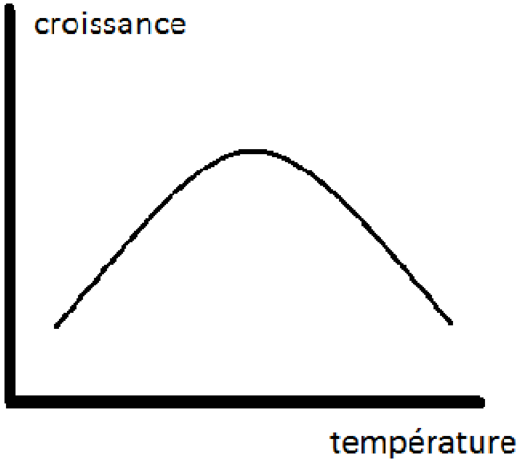
Effet sur la plante

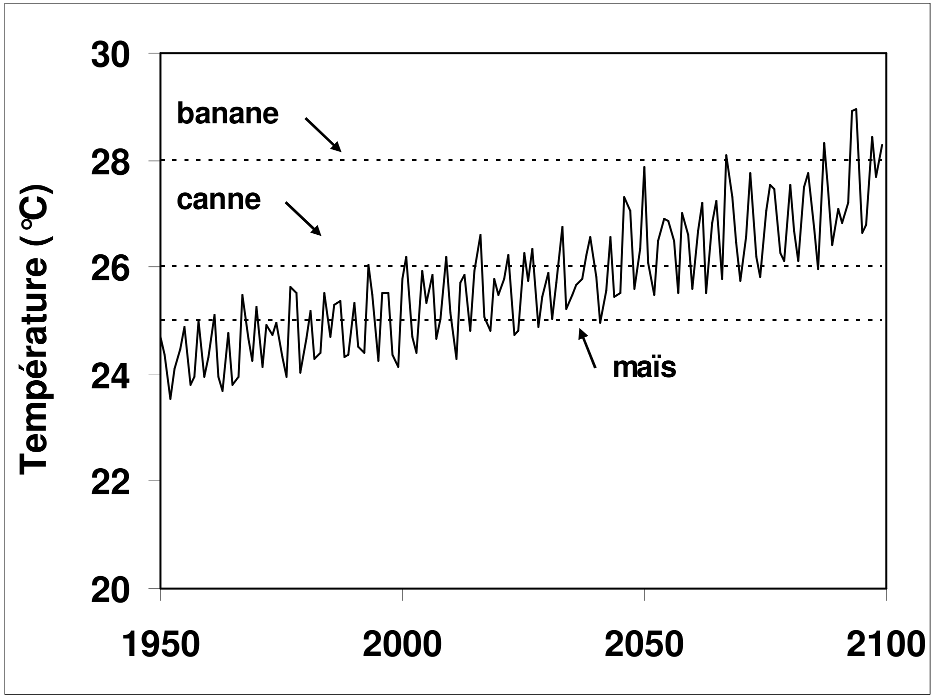
- ✓ Raccourcissement du cycle

  10-15% de réduction

- ✓ Taux de croissance

  Fonction de la culture

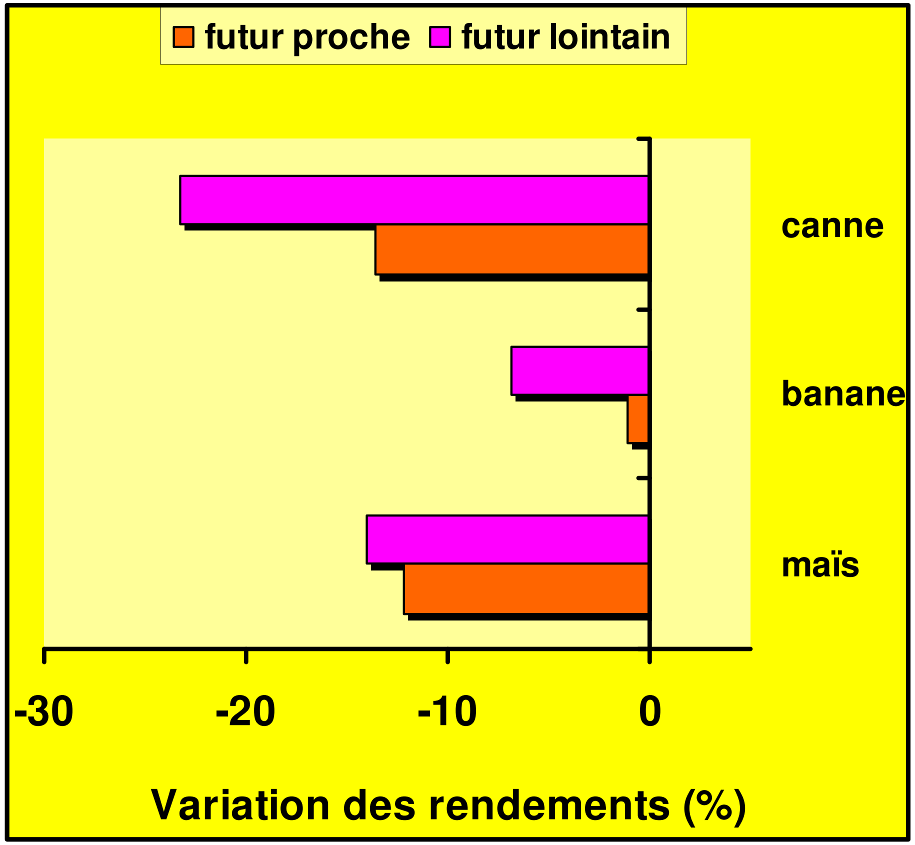




- ✓ Effet du CO_2

  Fonction de la culture

Effet sur la plante



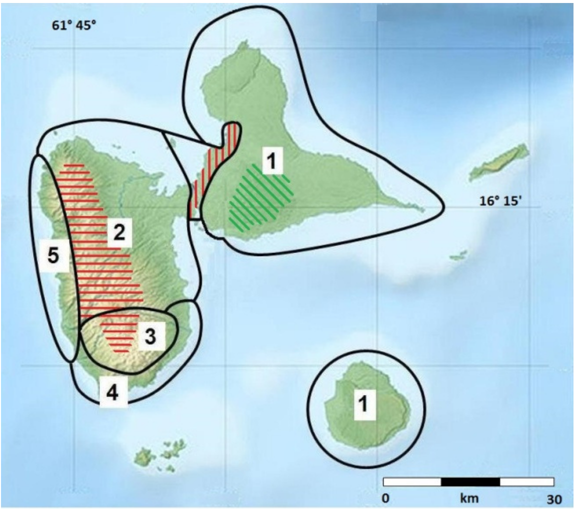
- ✓ Diminution des rendements :

  canne > maïs > banane

- ✓ Diminution du % de sucre chez la canne

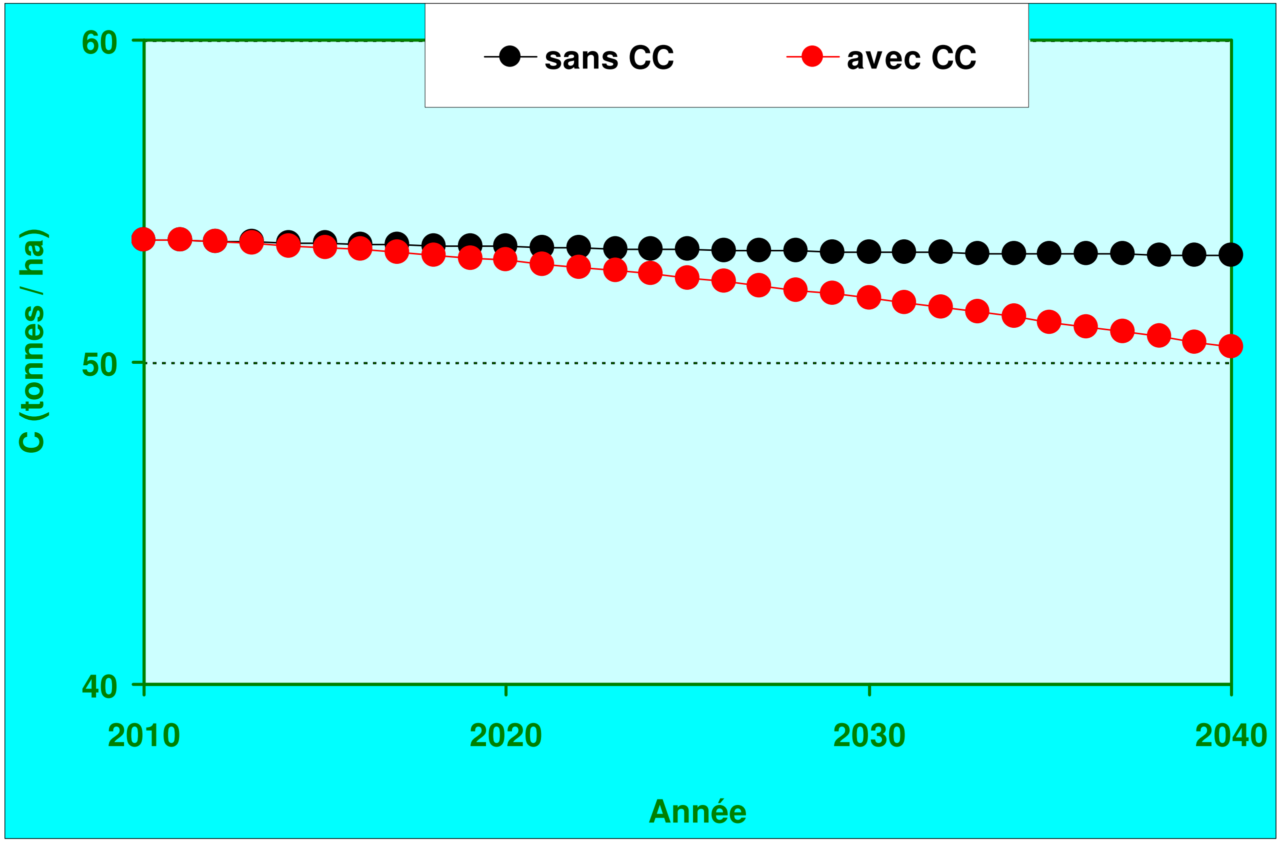
Résultats de TropEmis

- BD de Carib Agro avec 6000 analyses de sol
- 500 enquêtes et analyses de sols
- 253 parcelles suivies et évaluées depuis 1998
- 14 systèmes de culture analysés



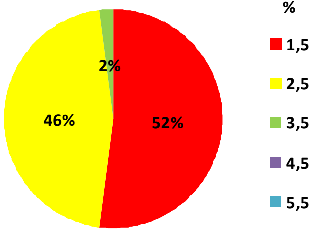
Simulation de l’effet du CC sur la MO

Canne à sucre, N Basse-Terre, rendement 60 tonnes/ha



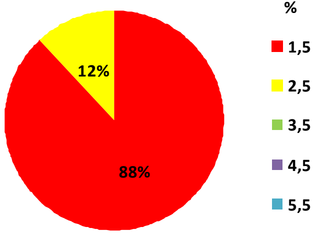
Impact du CC à l’horizon 2040 si l’on ne change rien

N-E Basse-Terre



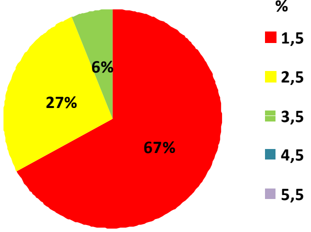
2010

N-E Basse-Terre



2040

Côte sous le vent



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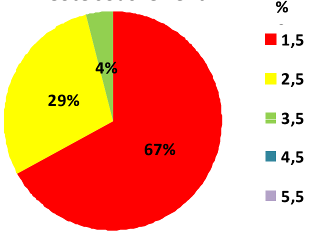
Côte sous le vent



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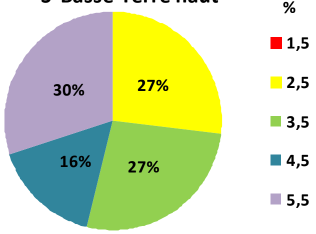
S Basse-Terre haut



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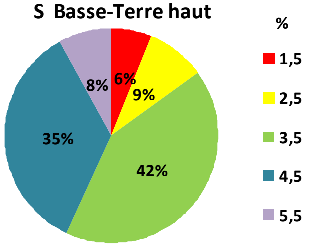
S Basse-Terre haut



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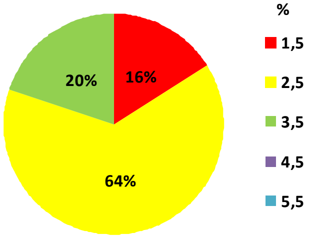
Grande-Terre



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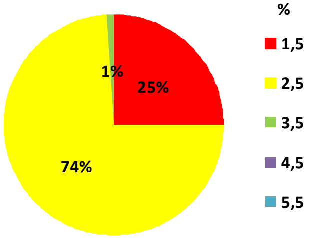
Grande-Terre



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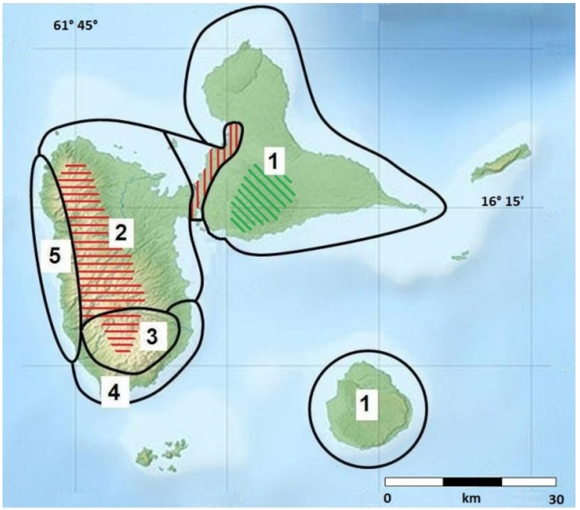
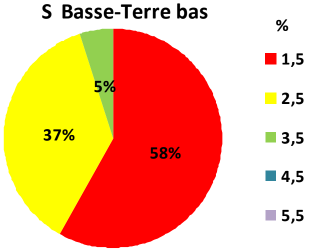


S Basse-Terre bas



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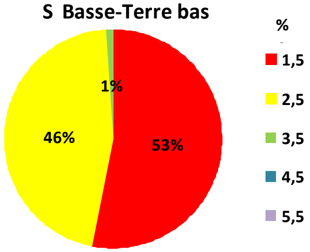
S Basse-Terre bas



2040

Réduction des impacts du CC sur la MO

- Augmentation des rendements (canne NBT)
- Réduction du travail du sol
- Application d'amendements organiques

Estimation de la quantité d'amendements nécessaire pour compenser l'impact du CC

Utilisation actuelle		21 000 t éq. compost / an
Pertes par CC	3 800 t C / an	
Pour combler ces pertes		51 000 t éq. compost / an
Besoin en amendement		72 000 t éq. compost / an

Il faut associer les pratiques !

Conclusions

- ✓ Attention ! des incertitudes fortes sur l'évolution des cyclones et des bio-agresseurs dans un climat plus chaud et humide

- ✓ Adaptations possibles :
  - ➢ augmentation de la biodiversité dans les systèmes
    biodiversité cultivée, polyculture-élevage
  - ➢ optimisation des itinéraires et des pratiques
    date de plantation, mulch, composts, travail du sol, etc.
  - ➢ amélioration génétique
    seuils de température ?

- ✓ Adaptation par rupture ?
  - ➢ *Prospective 2040 !*

Merci de votre attention !