Environmental assessment of agro-ecosystems. An integrated approach to manage agri-environmental risks.

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UNIVERSITE PIERRE ET MARIE CURIE

Paris 6

Habilitation à diriger des recherches

Dossier de candidature

présenté par

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L'évaluation environnementale des agrosystèmes : une approche intégrée pour gérer les risques agri-environnementaux.

Environmental assessment of agro-ecosystems. An integrated approach to manage agri-environmental risks.

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Chapitre 1

Le candidat

1.1 Résumé de carrière

NOM	Benoît GABRIELLE
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FORMATION

1996	Doctorat d'Energétique, Ecole Centrale Paris
1993	Diplôme d'Etudes Approfondies (D.E.A.) en Energétique, Ecole Centrale Paris
	Diplôme d'Ingénieur (spécialité : Thermique), Ecole Centrale Paris
1988	Baccalauréat Sciences Exactes, série C

CARRIÈRE SCIENTIFIQUE

Sept. 02 –	Promu Chargé de Recherche de première classe
Sept. 98 –	Chargé de Recherche dans l'Unité Mixte de REcherche
	Environnement et grandes cultures, Grignon
1998	Post-Doctorat de 6 mois à l'Université Cornell (NY, USA),
	dans le Department of Soil, Crop and Atmoshperic Sciences,
	sous la responsabilité du Professeur John M. Duxbury
1997-1998	Post-Doctorat à l'Institute of Arable Crops Research, Rothamsted
	sous la responsabilité de K. Goulding et T. Addiscott
1993-1996	Doctorat à l'Unité de Recherche en Bioclimatologie, INRA Grignon.
1993	Stage de D.E.A., Unité de Recherche en Bioclimatologie, INRA Grignon.

LANGUES	Anglais : bilingue	
	Allemand & Italien : lus & parlés	
	Notions d'Espagnol	
INFORMATIQUE	langages de programmation :	Fortran
	langages interactifs :	HTML, Javascript, CGI, Tcl/Tk
	logiciels :	Bureautique (MS Office, LaTeX) ;
		Traitement de données (Splus, R, ArcView)

1.2 Curriculum Vitae étendu

1.2.1 Activités de recherche

Elles sont détaillées dans le chapitre 2 de ce mémoire. Le paragraphe ci-dessous les résume et situe la thématique générale.
Depuis mon travail de thèse, mes thèmes de recherche ont porté sur l'évaluation environnementale des systèmes de grandes cultures, avec comme objectif l'identification de modes de gestion plus respectueux de l'environnement. L'originalité de l'évaluation, conduite sous forme d'un bilan environnemental, réside dans une prise en compte simultanée des impacts des pratiques sur les milieux sol, eau, et atmosphère. Cette démarche permet de minimiser les risques de transferts de pollution entre compartiments. Les impacts envisagés concernent les éléments carbone et azote, ainsi que les pesticides, à la fois pour les échanges gazeux, la rétention dans les sols et le rejet vers les eaux souterraines. La quantification des pertes environnementales repose pour une majeure partie sur un travail de modélisation des cycles bio-géochimiques dans les systèmes sol-plante, et, en parallèle, sur des expérimentations au champ pour tester les modèles. Ces derniers visant à appréhender les risques liés aux aléas climatiques, ils sont de nature dynamique et basés sur une description explicite des processus en jeu.

Mes activités de recherche sont structurées en trois grands volets : le développement de modèles intégrés de simulation des processus d'émission de polluants, à l'échelle du champ cultivé, avec un accent particulier sur les échanges gazeux. l'utilisation et la mise à disposition de ces modèles comme outils de diagnostic environnemental dans des contextes finalisés. la spatialisation des modèles pour obtenir des inventaires ou cadastres d'émissions sur un territoire plus large, ou régionaliser des recommandations issues du diagnostic.

1.2.2 Activités d'enseignement

Ma charge d'enseignement tend à s'accroître régulièrement, comportant à la fois des interventions ponctuelles et l'organisation de modules d'enseignement, au niveau Master. Les cours en 'face-à-face' représentent actuellement une quarantaine d'heures annuelles, réparties entre des ex-DEA (Ecologie - Paris XI et Biosphère continentale - Paris VI), Master 1ère année (Géo-Sciences - Marne-la-Vallée), les Master Européens Renewable Energy (Ecole des Mines de Paris) et CEWB (Ecole des Mines d'Albi), et l'INA P-G dans des Unités de Valeur de 2ème et 3ème année. Les thèmes de l'enseignement concernent l'évaluation environnementale intégrée des systèmes agricoles, la modélisation bio-physique, et la biomasse énergie, sous la forme de cours magistraux ou de TD.

Je suis responsable ou co-responsable de trois modules parmi les enseignements cités : Traitement des odeurs et des fumées (Master ParisTech Gestion et Traitement des Eaux, Sols et Déchets - 30h), bilan environnemental des produits phytosanitaires (DAA AGER, INA P-G - 18h), et Physico-chimie de l'environnement (Master Géo-sciences, Université de Marne-la-Vallée - 30h).

Enfin j'assiste le responsable du Master Professionnel ParisTech Gestion et Traitement des Eaux, Sols et Déchets, piloté par l'INA P-G. J'ai également participé à l'organisation de l'Ecole-Chercheurs du Département INRA Environnement & Agronomie : «pour une meilleure utilisation des modèles de culture» (automne 2002).

1.2.3 Encadrement d'étudiants

Le Tableau 1.1 récapitule les formations et noms des étudiants dont j'ai encadré le travail, du niveau bac à DEA ou Master. Concernant le niveau doctorat, j'ai encadré avec Enrique Barriuso (dans l'équipe "Sol" de mon UMR) le travail de thèse de Laure Mamy, soutenu le 1er Octobre 2004. J'encadre actuellement le travail de thèse de Marie-Noëlle Rolland, avec Pierre Cellier, Matthias Beeckmann (Laboratoire d'Aérologie, CNRS/Université Paris 6), et Patricia Laville. Je suis enfin 'co-encadreur à l'étranger' pour le doctorat de Waffa Rezzoug, à l'Université de Tiaret en Algérie.

J'ai également contribué de façon plus informelle à l'encadrement de quelques thésard(e)s :

- Bruno Leviel, thésard dans l'unité Bioclimatologie (j'ai été son encadrant principal pour l'obtention de son Diplôme de Recherche Universitaire- une sorte de pré-thèse - à l'INP Toulouse) ; thèse soutenue en 1999.
- Pedro Angas, thésard à l'ETSIA, Lleida (Espagne), qui a effectué un séjour de 3 mois à Grignon ; thèse soutenue en 2001.
- Daniela Mantineo, thésarde à l'Université de Catane (Italie), qui a effectué plusieurs séjours à Grignon ; thèse soutenue en 2003.
- Jérôme Cortinovis, thésard au laboratoire d'aérologie (Toulouse), pour un séjour de 2 mois à Grignon ; thèse soutenue en 2004.
- Caroline Sablayrolles, thésarde à l'ENSIACET (Toulouse) ; thèse soutenue en 2004.

Enfin j'ai fait ou fais actuellement partie de deux comités de pilotage de thèse (Macaire Edzangongo, INRA Grignon, et Luc Sorel, INRA Rennes).

TAB. 1.1 – Récapitulatif des étudiants encadrés (niveau bac à DEA).

Diplôme préparé	Période	Intitulé de la formation / Etablissement	Nom de l'étudiant(e)
Bac technique agricole	Un mois	Lycée agricole (78)	Mathieu Bazot
Bac technique agricole	Un mois	Lycée agricole (78)	Julien Varoquaux
Maîtrise de biologie	Un mois	Université Paris 6	Maggy Bardoux
Ingénieur agronome	9 mois	ISARA, Lyon	Jeanne Da-Silveira
Ingénieur agronome	8 mois	ESA Angers	Simon Lehuger
Ingénieur	6 mois	Ecole des Mines de Paris	Matthieu Delattre
Ingénieur	6 mois	Ecole des Mines de Paris	Kristel Hermel
Ingénieur	6 mois	Ecole Polytechnique Fédérale de Lausanne	Stéphanie Pérez
DESS Bio-Informatique	6 mois	Université Paul Sabatier Toulouse	Ghislaine Soumayet[1]
DEA Physique et Chimie de l'Environnement	6 mois	ENSEEIHT - INP Toulouse	Bruno Leviel
DEA de Biomathématiques	6 mois	Université Paris 6	Samira Bouzouina[1]
DEA d'Ecologie	6 mois	Université Paris 11	Emmanuelle Personeni
DEA Biosphère Continentale	6 mois	Université Paris 6	José Boronat[2]

[1] : co-encadrant : J.F. Martiné, CIRAD.
[2] : co-encadrante : C. Bedos, INRA.

1.2.4 Animation et gestion de la recherche

Animation scientifique Je participe depuis 1999 au réseau du Département Environnement & Agronomie (EA) animé par D. Wallach sur la modélisation du fonctionnement des cultures. Ce groupe de réflexion a débouché sur des séminaires méthodologiques et l'organisation d'une Ecole-Chercheurs en Octobre 2002, dans laquelle je me suis pleinement impliqué. Avec une autre membre du groupe (N. Brisson), nous avons aussi pris en charge l'organisation en Juillet 2004 de la session consacré à la modélisation des systèmes de cultures au cours du Congrès plénier de l'European Society for Agronomy. Actuellement, ce réseau modélisation est reconduit sous forme d'un projet de plate-forme INRA pour les modèles de culture, dont je fais partie du comité de pilotage.

Après la restructuration des Unités du Département EA sur Grignon, qui a conduit à la création de l'UMR Environnement et grandes cultures (EGC), j'ai pris en charge avec Pierre Benoit l'animation du projet transversal MAEVA ("Evaluation et maîtrise des risques agri-environnementaux"). Le projet n'a pas abouti dans sa totalité (certainement trop ambitieuse !), mais a permis de démarrer la thématique sur le bilan environnemental des herbicides et le travail de thèse de L. Mamy. Au niveau de mon équipe scientifique (comprenant une vingtaine de permanents), j'ai fait partie du collège de 3 chercheurs qui a assumé la direction d'équipe période fin 2002 - début 2004. Depuis un an j'anime un groupe d'ingénieurs et techniciens en charge des différentes stations météorologiques gérées par l'Unité, dont le parc météo qui fait partie du réseau INRA AgroClim d'observations météorologiques.
J'ai été ou suis encore membre de divers Conseils Scientifiques (UMR Environnement et grandes cultures, Département AGER de l'INA P-G, Département Environnement&Agronomie de l'INRA, et INRA), et de Gestion (Centre INRA Versailles-Grignon).

Montage de projets J'ai été ou suis actuellement partenaire dans un certain nombre de projets au niveau national (une dizaine depuis 1998), ou Européen. Je fais partie du réseau d'excellence 'BioEnergy' du 6ème programme cadre, pour lequel je coordonne le 'Work Package' AgroBiomass, et du projet intégré NitroEurope, qui vient de démarrer. J'assure actuellement la coordination de deux projets financés par le consortium Agrice et par l'INSU / CNRS sur le bilan environnemental des applications d'herbicides dans un contexte d'introduction de cultures génétiquement modifiées résistantes à des herbicides à large spectre.

Evaluation J'expertise deux à trois articles par an pour des revues internationales (Agronomie, Agronomy Journal, Australian Journal of Agronomy, Environment International, European Journal of Agronomy, Journal of Environmental Management, Journal of Environmental Modelling and Software, Journal of Environmental Quality, Plant and Soil, Soil Science Society of America Journal).
J'ai également expertisé des projets pour le Département INRA EA (projets innovants, en 2003 et 2004), le Fonds de Recherche sur la Nature et les Technologies du Québec (2004), le Binational Agricultural Research and Development Fund (Israël / USA - 2004), et la Fondation pour la Science et la Technologie du Portugal (2005).
J'ai enfin participé à un jury de concours CR1 en 2004, et fait partie de la commission d'évaluation du laboratoire INRA de microbiologie des sols de Dijon en 2005.

1.2.5 Expertise

J'ai participé à un groupe de travail ADEME-ACTA, puis à l'expertise collective INRA sur *les potentialités de stockage de carbone des sols agricoles en France* (30). J'ai été membre du groupe de travail 'Indicateurs' du CORPEN (Comité d'Orientation pour des Pratiques agricoles respectueuses de l'Environnement), au Ministère de l'Environnement. J'ai coordonné avec Pascal Mallard (CEMAGREF, Rennes) une étude commanditée par l'ADEME sur les impacts environnementaux de la gestion biologique des déchets(77). L'objectif était de faire un bilan des connaissances disponibles, et de leur insertion possible dans une démarche de type 'analyse de cycle de vie'. Les résultats sont actuellement repris dans des bases de données utilisées au niveau international, comme EcoInvent.

Enfin je consacre une partie de mon travail au transfert des modèles et méthodes d'évaluation environnementale, que ce soit vers des partenaires scientifiques ou techniques (INRA, CIRAD, CEMAGREF, CETIOM, Arvalis, ENSIACET), ou des étudiants. Le transfert passe par la conception et mise à disposition d'outils de simulation et de leurs interfaces, pour rendre leur utilisation accessible aux gens qui ne sont pas spécialistes de la modélisation. Une démonstration du modèle CERES-Maïs a ainsi été mise en place sur Internet (*www-egc.grignon.inra.fr/ceres_mais/tpCeres.html*).

1.3 Liste des publications

Les noms des étudiants que j'ai encadrés sont indiqués en italique.

Publications scientifiques

Articles dans revues à comité de lecture / Peer-reviewed articles

[1] **B. Gabrielle**, S. Menasseri, and S. Houot. Analysis and field-evaluation of the CERES models' water balance component. *Soil Sci. Soc. Am. J. 59 :1402-1411*, 1995.

[2] **B. Gabrielle** and L. Kengni. Analysis and field-evaluation of the CERES models' soil components : Nitrogen transfer and transformation. *Soil Sci. Soc. Am. J. 60 :142-149*, 1996.

[3] **B. Gabrielle**, P. Denoroy, G. Gosse, E. Justes, and M. N. Andersen. Development and evaluation of a CERES-type model for winter oilseed rape. *Field Crops Res. 57 : 95–111*, 1998.

[4] **B. Gabrielle**, P. Denoroy, G. Gosse, E. Justes, and M. N. Andersen. A model of leaf area development and senescence for winter oilseed rape. *Field Crops Res. 57 : 209–222*, 1998.

[5] *B. Leviel*, **B. Gabrielle**, E. Justes, B. Mary, and G. Gosse. Water and nitrate budgets in a rapeseed cropped rendizina soil receiving different amounts of fertiliser. *Eur. J. Soil Sci. 49 : 37–51*, 1998.

[6] **B. Gabrielle** and S. Bories. Theoretical appraisal of field-capacity based infiltration model and their scale parameters. *Transport Porous Med. 35 : 129–147*, 1999.

[7] G. Gosse, P. Cellier, P. Denoroy, **B. Gabrielle**, P. Laville, *B. Leviel*, B. Nicolardot, E. Justes, B. Mary, S. Recous, J.C. Germon, C. Hénault, and P.K. Leech. Water, carbon and nitrogen cycling in a rendzina soil cropped with winter oilseed rape : the Châlons Oilseed Rape Database. *Agronomie 19 : 119-124*, 1999.

[8] E. Justes, P. Denoroy, **B. Gabrielle**, and G. Gosse. Effect of crop nitrogen status and temperature on the radiation use efficiency of winter oilseed rape. *Eur. J. Agron. 13 : 165-177*, 1999.

[9] **B. Gabrielle**, F. Agostini, and M. Donatelli. Limits to the accuracy of the water component of a decision-support-oriented agronomic model. *Italian J. Agron. 3 : 87-99*, 2000.

[10] **B. Gabrielle**, S. Recous, G.S. Tuck, N.J. Bradbury, and B. Nicolardot. Ability of the SUNDIAL model to simulate the short-term dynamics of 15N applied to winter wheat and oilseed-rape. *J. Agric. Sci. (Camb) 137 : 157-168*, 2001.

[11] C. Bedos, P. Cellier, R. Calvet, E. Barriuso, and **B. Gabrielle**. Mass transfer of pesticides into the atmosphere by volatilization from soils and plants : overview. *Agronomie*, 22 :21–33, 2002.

[12] **B. Gabrielle**, B. Mary, R. Roche, P. Smith, and G. Gosse. Simulation of carbon and nitrogen dynamics in arable soils : a comparison of approaches. *Eur. J. Agron. 18 : 107-120*, 2002.

[13] **B. Gabrielle**, R. Roche, *P. Angas*, C. Cantero-Martinez, L. Cosentino, *M. Mantineo*, M. Langensiepen, C. Hénault, P. Laville, B. Nicoullaud, and G. Gosse. A priori parameterisation of the CERES soil-crop models and tests against several european data sets. *Agronomie 22 : 119-132*, 2002.

[14] **B. Gabrielle**, *J. Da-Silveira*, S. Houot, and C. Francou. Simulating urban waste compost impact on C-N dynamics using a biochemical index. *J. Envion. Qual. 33 :2333-2342*, 2004.

[15] **B. Gabrielle**, *J. Da-Silveira*, S. Houot, and J. Michelin. Field-scale modelling of C-N dynamics in soils amended with municipal waste composts. *Agric. Ecosys. Environ.*, 110 :289–299, 2005.

[16] C. Hénault, F. Bizouard, P. Laville, **B. Gabrielle**, B. Nicoullaud, J. C. Germon, and P. Cellier. Predicting *in situ* soil N2O emissions using NOE algorithm and soil data base. *Global Change Biol. 11 : 115-127*, 2005.

[17] P. Laville, C. Hénault, **B. Gabrielle**, and D. Serça. Measurement and modelling of no fluxes on maize and wheat crops during their growing seasons : effect of crop management. *Nutr. Cycling Agroeco.*, 72 :159 – 171, 2005.

[18] L. Mamy, E. Barriuso, and **B. Gabrielle**. Environmental fate of different herbicides : trifluralin, metazachlor, metamitron and sulcotrione, compared to that of glyphosate, a broad-spectrum herbicide, for different glyphosate-resistant crops. *Pest Manag. Sci.*, 61 :905–916, 2005.

Articles soumis / In review

[19] C. Bedos, M. F. Rousseau-Djarbi, **B. Gabrielle**, D. Flura, B. Durand, E. Barriuso, and P. Cellier. Measurement of trifluralin volatilization in the field : relation to soil residue and effect of soil incorporation. *submitted to Chemosphere (5 Sep. 2005)*, 2005.

[20] **B. Gabrielle** and N. Gagnaire. Life-cycle assessment of straw use in bio-ethanol production : a case-study based on deterministic modelling. *submitted to Biomass and Bioenergy (25 Aug. 2005)*, 2005.

[21] **B. Gabrielle**, P. Laville, C. Hénault, B. Nicoullaud, and J. C. Germon. Simulation of nitrous oxide emissions from wheat-cropped soils using CERES. *submitted to Nutr. Cycl. Agroecoecos. (12 Sep. 2005)*, 2005.

Articles dans revues sans comité de lecture / General articles

[22] **B. Gabrielle**. Mesure et modélisation du bilan environnemental du colza. *Oléagineux, Corps Gras, Lipides 4 : 220–227*, 1997.

[23] Z. Popova, *B. Leviel*, T. Mitova, **B. Gabrielle**, and M. Kercheva. Calibration and validation of CERES model of wheat ecosystem located in Sofia region. *J. Balkan Ecology 3 : 53-61*, 2000.

[24] Z. Popova, M. Kercheva, *B. Leviel*, and **B. Gabrielle**. CERES model application to assess nitrogen leaching in wheat ecosystem. *J. Balkan Ecology 3 : 62-67*, 2000.

[25] Z. Popova, M. Kercheva, **B. Gabrielle**, and *B. Leviel*. Test of the biological module of Ceres-Maize model in lysimeters on chromic luvisol. *Soil Sci. Agrochem. Ecol. 36 : 105-110*, 2001.

[26] *B. Leviel*, C. Crivineanu, and **B. Gabrielle**. CERES-Beet, a prediction model for sugar beet yield and environnemental impact. *Adv. Sugar Beet Res., 5 : 143-152*, 2003.

[27] J.C. Germon, C. Hénault, P. Cellier, D. Chèneby, O. Duva, **B. Gabrielle**, P. Laville, B. Nicoullaud, and L. Philippot. Les émissions de protoxyde d'azote (N_2O) d'origine agricole. evaluation au niveau du territoire français. *Etude et Gestion des Sols 10 : 315-328*, 2003.

Chapitres d'ouvrages / Book chapters

[28] G. Gosse, P. Cellier, P. Denoroy, **B. Gabrielle**, P. Laville, *B. Leviel*, B. Nicolardot, E. Justes, B. Mary, S. Recous, J.C. Germon, and C. Hénault. Modélisation du bilan environnemental d'une

culture de colza. In P. Maillard and R. Bonhomme, editors, *Fonctionnement des peuplements végétaux sous contraintes environnementales*, pages 117–134. Les colloques de l'INRA no 93, INRA Editions, Paris, 2000.

[29] **B. Gabrielle**. Analyse d'incertitudes de composantes statique et dynamique d'un modèle de culture. In D. Wallach, editor, *Pour une meilleure utilisation des modèles de culture*. Département E&A, INRA (support de cours), 2002.

[30] **B. Gabrielle**. Rôle de la consommation d'intrants dans le bilan agricole de gaz à effet de serre. In D. Arrouays, J. Balesdent, J.C. Germon, P.A. Joyet, J.F. Soussana, and P. Stengel, editors, *Stocker du carbone dans les sols agricoles de France ?*, pages 89–92. INRA Expertise Scientifique Collective, 2002.

[31] **B. Gabrielle**. Sensitivity and uncertainty analysis of a static denitrification model. In D. Wallach, Makowski, and J.W. Jones, editors, *Working with crop models. Evaluating, analyzing, parameterizing and using them* , page A paraître. Elsevier, 2005.

[32] J.L. Dupouey, D. Arrouays, **B. Gabrielle**, G. Gosse, J.F. Soussana, and B. Seguin. L'effet de serre : le cycle du carbone et la biomasse. In P. Colonna, editor, *Chimie Verte*. Collection Techs et Doc, Lavoisier (in the press), 2005.

[33] C. Hénault, P. Roger, P. Laville, and **B. Gabrielle**. La contribution des sols aux émission des gaz à effet de serre CH4 et N2O. In M.C. Girard, C. Walter, J.-C. Rémy, J. Berthelin, and J.-L. Morel, editors, *Sols et environnement. Cours et études de cas*. Sciences Sup, Dunod, Paris, 2005.

[34] A. Jullien, R. Roche, M.H. Jeuffroy, **B. Gabrielle**, and P. Huet. Intérêts de l'utilisation conjointe des modèles ceres et azodyn pour raisonner la modulation de la fertilisation azotée. In Guérif M., editor, *Vers une agriculture de précision - Hétérogénéité parcellaire et gestion des cultures*. INRA Editions (in the press), 2005.

[35] R. Roche R., A. Jullien, **B. Gabrielle**, and P. Huet. Modulation azotée : gains potentiels et aléas - utilisation du modèle ceres pour analyse les conséquences environnementales de différentes stratégies de fertilisation azotée dans des rotations colza-blé. In Guérif M., editor, *Vers une agriculture de précision - Hétérogénéité parcellaire et gestion des cultures*. INRA Editions (in the press), 2005.

Analyse d'ouvrages / Book review

[36] **B. Gabrielle**. Handbook of processes and modeling in the soil-plant system : A book review. *Agricultural Systems 82 : 195-196*, 2004.

Conférences / Conference proceedings

[37] **B. Gabrielle**, G. Gosse, and B. Leviel. Bilan environnemental du colza : méthodologie expérimentale et modélisation. In *Actes des Journées du Programme Environnement, Vie et Sociétés, 15-17 Janvier 1996*, pages 144–148, 1996.

[38] **B. Gabrielle**, N. J. Bradbury, B. Nicolardot, H. Svendsen, J. U. Smith, S. Hansen, and G. Gosse. Simulation of N dynamics in a rapessed-cropped rendzina soil with the CERES, DAISY and SUNDIAL models. In O. van Cleemput et al., editor, *Fertilization for sustainable plant production and soil fertility, Proc. 11th Internat. World Fertilizer Congress, Gent, BL, 7-13 Sept.*, pages 88–95. CIEC, Braunschweig, 1997.

[39] **B. Gabrielle**, G. Gosse, and B. Nicolardot. Différentes échelles de temps et de complexité dans la modeling des bilans environnementaux des cultures. In *Actes des Journées du Programme Environnement, Vie et Sociétés, 5-7 Novembre 1997, Toulouse*, pages 89–95. CNRS, 1997.

[40] *B. Leviel*, **B. Gabrielle**, E. Justes, B. Mary, B. Nicolardot, and G. Gosse. Some results and modeling of water and nitrate budgets under oilseed rape receiving different amounts of fertilizer. In O. van Cleemput et al., editor, *Fertilization for sustainable plant production and soil fertility, Proc. 11th Internat. World Fertilizer Congress, Gent, 7-13 Sept.*, pages 339–343. CIEC, Braunschweig, 1997.

[41] **B. Gabrielle**, E. Justes, and P. Denoroy. Modelling of temperature and nitrogen effects on the rooting dynamics of winter oilseed rape. In ISSS, editor, *Proc. International Society of Soil Science Congress, Aug. 1998, Montpellier, France*, 1998.

[42] **B. Gabrielle**, R. Roche, and G. Gosse. CERES-Rape, a model for the production and environmental impact of rapeseed. In *Proc. 10th International Rapeseed Congress, Sept. 99, Canberra, Australia.*, 1999.

[43] **B. Gabrielle**, R. Roche, *P. Angas*, S. Cosentino, *M. Mantineo*, M. Langensiepen an C. Hénault, P. Laville, B. Nicoullaud, and G. Gosse. Extrapolation of soil-crop models across Europe : is model structure still relevant compared to parameterization ? In M. Donatelli et al., editor, *Modelling cropping systems, Proc. ESA Congress, June 1999, Lleida, Spain*, 1999.

[44] *P. Angas*, **B. Gabrielle**, and C. Cantero-Martinez. Crop growth and soil water and nitrogen dynamics, as affected by tillage and fertiliser nitrogen under semi-arid conditions. Simulation by CERES-Barley. In M. Donatelli et al., editor, *Modelling cropping systems, Proc. ESA Congress, June 1999, Lleida, Spain*, pages 133–134, 1999.

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Chapitre 2

Synthèse des travaux / Summary of past research

2.1 Background, objectives and methodology

In the aftermath of the great economic and technological boom of the 1950's and 1960's, the Western world gradually awoke to the fact that natural resources only existed in limited supply, and also had a limited capacity to filter out the pollutants released by human activities. This concern was rapidly shared by the rest of the world, faced with global issues like climate changes or stratospheric ozone depletion. Among human activities, agriculture has come into sharp focus because it covers around 10% of terrestrial land, and is associated with increased use of inputs with potential damage to the environment (Table 2.1). Agriculture thus crystallizes the apparent dilemma between the production push and the environmental pull, often cited as antagonistic (76; Tilman et al., 2002)[1]. The global demand for food and feed products is expected to increase 50% by 2020, while yields are levelling off in most parts of the world, and the area of land potentially convertible for arable production is only marginal (Tilman et al., 2002). Agriculture is also expected to be an increasing player in the field of renewable energy, with a high potential to substitute declining fossil resources. Given this increasing demand for agricultural outputs, there is a clear need to improve and possibly optimize the environmental performance of agricultural production systems.

During the past 12 years, my research has focused on the environmental assessment of agricultural activities, in order to find ways of improving the performance of agro-ecosystems. The starting point was the 1992 reform of the European Common Agricultural Policy, which enforced obligatory set-aside land for farmers, while allowing them to grow energy crops on it. Those crops provided in principle significant leverage for mitigating global warming by displacing the use of fossil fuels, in particular liquid fuels for transport for which few renewable alternatives to fossil oil exist. However, since energy supply is not the primary function of agriculture, ensuring that energy crops had little impacts on the environment was a pre-requisite to their development. Hence the need for a comprehensive and rational framework for evaluating these impacts.

The assessment I developed is based on an **environmental balance** that considers a range of impacts on the soil, water, and atmospheric compartments. This balance approach makes it possible to optimize environmental performance while **minimizing the trade-offs between different types of pollutions** (32). The management variables I tested included the management of individual crops (sowing date, fertiliser N application, irrigation), cropping systems (rotations, intervals between two

[1] In the following, the references cited as number refer to my publication list (section 1.3), while those in the author-year format appear in the reference list of Chapter 4.

TAB. 2.1 – Major impact categories and pollutants associated with agricultural inputs. Note that agriculture may be a source as well as a sink of pollutants. Ecological impacts such as erosion, biodiversity and landscape quality are not included.

Impact category	Pollutants	Agricultural practice involved
Depletion of non-renewable resources	–	Use of synthetic inputs & machinery
Global warming	N_2O, CH_4, CO_2	Application of fertilizer N, organic amendments, bio-energy
Acidification	NH_3, NO_x	Application of fertilizer N
Photochemical ozone creation	NO_x	Application of fertilizer N
Eutrophication	NO_3^-, NH_3, P	Application of N and P fertilizers
Toxicity & Human health	Heavy metals, Persistent organic pollutants	Application of pesticides & organic amendments

successive crops), and final use (*e.g.* bio-energy or animal feed).

The idea that the environmental balance of agricultural practices may be optimized is illustrated on Figure 2.1, which shows how the N fertilizer rate applied to a winter oilseed rape crop in northern France influences various N losses of environmental relevance. The latter encompass nitrate leaching, ammonia (NH_3) volatilization and nitrous oxide (N_2O) emissions. Ammonia is involved in impacts such as natural ecosystems eutrophication and soil acidification, while N_2O is a greenhouse gas (Table 2.1). Figure 2.1 presents the latter fluxes, as measured during a dedicated field experiment (5) for three N fertilizer rates : no N (control), a rate based on an agronomic N balance method, and a supra-optimal rate. Because our objective was to minimize the marginal environmental impacts of crop production, the N fluxes were divided by the final grain yields achieved by each treatment. Figure 2.1 shows the intermediate (agronomically sensible) N rate to be optimal as far as nitrate leaching was concerned, whereas the unfertilized control performed best regarding gaseous losses. As could be expected, the supra-optimal treatment came out as the worst option in terms of environmental impact. However, none of the other two treatments emerged as clearly optimal. Also, the picture in Figure 2.1 is only partial since the environmental costs associated with the manufacturing and transport of synthetic fertiliser N should also be included in the comparison of the various N treatments.

Such is actually the purpose of life cycle assessment (LCA), a concept which embeds the environmental balance, and was originally developed in the chemical industry to optimize the packaging of drinks (Hunt et al., 1974). The objective of LCA is to estimate the impacts resulting from the production of particular good or service, through its entire life-cycle 'from cradle to grave' (i.e. from the extraction of raw materials to the recycling or disposal of the product considered). The results are expressed relative to a measure reflecting the usefulness of the product system, called 'functional unit'. As standardized in the late 1990's (ISO, 1997), LCA comprises four stages : system definition, inventory energy and matter flows (including environmental contaminants) occurring throughout the product's life-cycle, characterization of the potential impacts associated with the emission of pollutants, which are subsequently grouped into broad impact categories such as global warming, and lastly interpretation and system optimization.

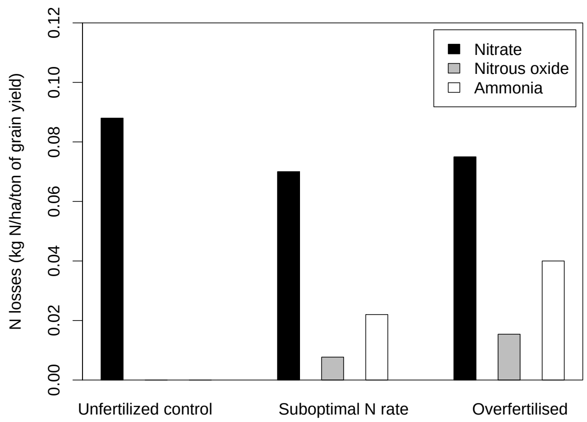


FIG. 2.1 – Measured N fluxes under an oilseed-rape crop receiving various levels of fertiliser N (5). The fluxes are expressed relative to one ton of rapeseed grains, which is the functional unit of this agricultural system. An optimum is visible for the suboptimal fertilizer rate.

As public and private bodies such as ADEME[2], advisory and extension services, local authorities, or waste and water treatment companies grew aware of the need for a standardized appraisal of environmental performances, there appeared a need to implement LCA for goods and services whose life cycle includes an agricultural phase - a major shift since LCA was originally developed in the industry. Because of the complexity of natural agro-ecosystems, this adaptation brought about a host of new research issues for research organizations like INRA in France (Gosse, 1998). Application of LCA to agricultural systems namely requires :

A **simultaneous** prediction of pollution fluxes resulting from the use of agricultural inputs, at the field level. This implies detailed knowledge of the processes at stake, and a capacity to model their determinism within an agro-ecosystem.

B prediction of **actual impacts** resulting from these emissions.

C comparison of these direct impacts with those associated with industrial operations upstream and downstream from the arable field, referred to as **indirect impacts** (manufacturing of agricultural inputs, transport, transformation of harvested products, etc...)

D identification of crop management options that may **mitigate direct emissions** and those of the whole chain.

Such were the issues behind my past research activities within INRA, with more specific application to bio-fuel chains (in comparison with fossil equivalents), urban waste composting (vs. incineration or landfill disposal of waste), and chemical crop weeding strategies, as exemplified in section 2.6.

Given the range of research and development issues raised by the above points, the small group I have been working in within my laboratory has focused on two particular points, one research-orientated and the other more application-driven. In connection with point *A* above, my core research was dedicated to the impacts involved with the dynamics of water, carbon, and nitrogen, as well as pesticides, in the soil-plant-atmosphere system. This work mostly involved the field-scale, and will be central in this report.

In parallel, our group developed some skills on point *C*, which involved the maintenance of data bases on agricultural inputs and transformation processes, as well as the use of dedicated LCA software to cover the whole chain considered. This benefited from collaborations with other European Institutes dealing with LCA, and also french Agencies and advisory institutes.

[2]ADEME is the french Environment and Energy Management Agency

To conclude on the above listed issues, point *B* implies a coupling of field-scale models with higher-scale models that simulate the transport and transformations of the pollutants released to mid-point or end-point targets (water streams, human populations, etc..), whether by waterways or airways. The exposure of these targets may then be calculated, and a final effect computed through exposure-effect relationships. Although we have chosen to ignored that part up to now, tackling it has emerged as a critical issue to improve our predictions of local impacts (in particular ecotoxicity), and will be discussed in the section dealing with future research plans (Chapter 3).

Prior to giving the specifics of my work within the framework of LCA, the following section puts the issues of environmental assessment in agro-ecosystems into a broader perspective, by reviewing other approaches and how they may connect with or complement LCA, particularly regarding the issue of decision-support.

2.2 Which methodology for environmental assessment ?

As emphasized in the above section, we are here concerned with methods that tackle the range of impacts caused by agricultural management of arable land, and not a single particular issue such as global warming or drink water quality. Secondly, we are looking at methods that make it possible to optimize a given agricultural system relative to crop production. That is to say we need an estimate of the productivity achieved by the system with the management strategies considered, the overall objective being to minimize the marginal environmental impacts incurred by the production of one unit of marketable biomass.

2.2.1 Current methods

There exists a host of methods currently available for environmental assessment, as recently reviewed by Capillon et al. (76). They may be classified according to various criteria, including their complexity, the domain they cover in terms of variability or environmental issues, or their orientation towards decision-support. Figure 2.2 uses spatial and temporal variability as the main entry in such classification, and breaks down the methods into three main groups :

- the technical methods, based solely on technical management information, and ignoring the effects of the physical environment (soil and climate types) in which they are applied ;
- the methods based on fluxes of energy and matter, which have the potential to fully account for the effects of physical environment ;
- and the intermediate methods, which use a mix of management and environmental information.

The technical and intermediate methods are easier to implement and more fit to decision-making than the flux-based methods. Not only are the latter more complex by nature, but they output relationships between crop management and environmental impacts that are blurred to a large extent by environmental conditions. However, this reflects the reality of the agricultural systems, which react in vastly different ways to a given set of management options. Ignoring spatial and temporal variability in the assessment may then lead to the wrong decisions. Also, the fluxes of matter and energy at the bases of the complex methods may be measured directly in the field for validation purposes, wheres the other methods may only be checked from a qualitative point of view ((Bockstaller and Girardin, 2003)). The result is that accuracy and applicability are viewed as conflicting traits of environmental assessment methods, between which some trade-off should be accepted by users (76).
I would rather advocate some degree of complementarity between the various available methods. For

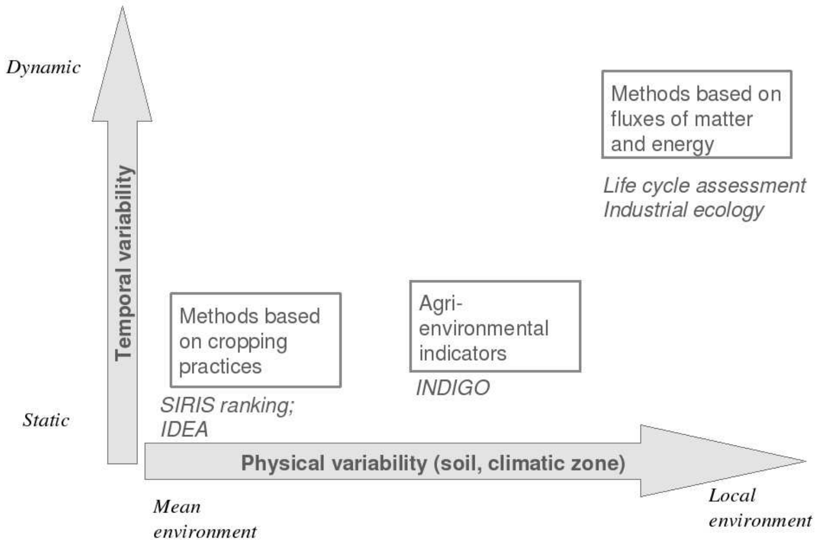


FIG. 2.2 – Proposed classification of environmental assessment methods, showing the extent to which temporal and spatial variability are taken into account. References for the cited examples : SIRIS (Vaillant et al., 1995), IDEA (Vilain, 2003), INDIGO (Girardin et al., 1999).

instance, flux-based methods may be run on a set of scenarios reflecting the variability of the geographical domain of interest to derive local recommendations at a relatively low cost (such is currently the case with pesticide approval (FOCUS, 2000)). One could also consider a tiered system of evaluation, with simpler methods used to screen a wide range of scenarios, and saving the more complex approaches for further analysis of the most critical scenarios. Lastly, flux-based methods cannot evaluate more qualitative impacts, such as biodiversity or landscape quality - in which case other methods should be developed to complement the system appraisal, based on other disciplines (eg, soil microbiology or ecology).

2.2.2 Research issues with flux-based methods

In principle, the methods based on fluxes of energy and matter should rely heavily on process-oriented modelling, since the latter is the only approach available that explicitly addresses the variability in agro-ecosystems functioning. To date, however, such is not the case in practice since most published results on LCA in agriculture merely use fixed factors to convert agricultural inputs into environmental emissions (Brentrup et al., 2001; Mendes et al., 2003), or simple elemental balances (Audsley, 1997). This is most likely due to the lack of adequate models in terms of emissions considered and user-friendliness, and also of detailed reference input data on soil, climate and crop management over the geographical area considered. However, it is my belief that recent progress in these three areas bodes well for future improvement in LCA along these lines - as show preliminary results presented further on in this report (section 2.6.1). Therein lies a major challenge for future research on environmental assessment.

Application of biophysical models in the above-mentioned context requires to go through a sequence of stages, as illustrated on Figure 2.3, including :

– **development of integrated models** that simulate emission processes at the field scale - which may more appropriately be considered as the integration of new processes or approaches in

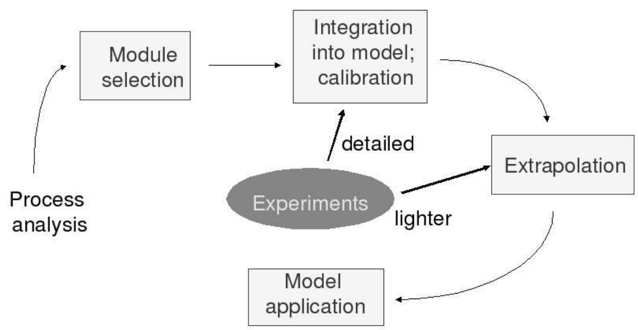


FIG. 2.3 – The various stages of modelling from process integration to final application.

existing models ;
– **detailed testing** of the resulting models against experimental data that allow a check of individual model components ;
– **multi-local testing** on a network of less detailed field experiments, prior to extrapolating models on a wider scale ;
– **application of models** for scenario analysis and environmental assessment.

Along with the central box on experimental data, the modelling stages make up the backbone of my past activities, and provide the outline for their description in the following sections.

2.3 Building new models or building on old ones ?

2.3.1 Background and approach to model development

Since its early stages in the late 1970's, the modelling of cropping systems has gradually become part of most research projects dealing with agricultural systems (Boote et al., 1996). The number of processes and cropping systems for which models are available has been constantly increasing, as has been the range of agronomical- or environmental-oriented applications. These include for instance regional and national inventories of greenhouse gas budgets (Falloon et al., 1998; Mummey et al., 1998; Smith et al., 2000), the impact of climate change on agriculture (Ewert et al., 1999; Rosenzweig and Parry, 1994), integrated environmental assessment of agricultural practices (Pang et al., 1998; Yiridoe et al., 1997), land-use change scenarios (Mummey et al., 1998; Sitompul et al., 1996), or precision agriculture (Sadler et al., 2000).

Although some of these applications directly relate to the issue at hand here, such was not the case in the early 1990's when I started working on my Ph.D. There was (and I believe still is somewhat) a discrepancy between environment-orientated models, which were developed by scientists working jointly (or not !) within the disciplines of soil physics, soil chemistry, and soil ecology, and production-orientated models, driven by eco-physiologists and agronomists. Examples of these early models include PRZM (Carsel et al., 1985), LEACHM (Wagenet and Hutson, 1989), and DAISY (Hansen et al., 1993) for the former category, and EPIC (Williams and Sharpley, 1989), CERES (Jones and Kiniry, 1986), and SUCROS (Spitters et al., 1989) for the latter. As Dr. S.R.C. Rao (Univ. Florida) put it in a conversation we had around that time, "we [*soil scientists*] trivialize the crop, and they [*agronomists*]

trivialize the soil".
The CERES model, released in the mid-1980's, provided an interesting attempt at bridging this divide since it resulted from a joint effort between ecophysiologists and soil physicists. The approaches taken to simulate the various processes included in this model struck a good balance between the various components, in terms of complexity and scientific soundness. I thus started working within the CERES framework, focusing on the simulation of water, carbon and nitrogen dynamics in soil-crop systems. However, model testing under french conditions quickly revealed some problems with model components like soil organic matter (OM) turnover, water infiltration in the soil profile, or denitrification. This prompted me early on to keep a close watch on the development of other models being used for similar purposes, against which the performance of CERES could be benchmarked and possibly improved. Eventually, this kind of comparison lead me to modify some of the model components. Also, when some other component was unavailable within CERES, I had to either import them from other models, or build them from scratch.

The following paragraphs illustrate these various modelling tasks : i/ comparison of performance at model or module[3] level, ii/ modification of a particular module and subsequent test, and iii/ development of new modules.

2.3.2 Comparison of modelling approaches

Model comparison may take place at global (ecosystem) or module level, and may serve several purposes : providing guidance to potential users in model selection, benchmarking of models, or assessing the respective merits of various approaches for modelling particular processes. Most published comparisons involve the global level, and consisted in running various models against series of independent data sets (de Willigen, 1991; Diekkrüger et al., 1995; Smith et al., 1997). These exercises provide valuable information on the overall performance of these models. For instance, they make it possible to judge the trade-off between model complexity and accuracy, since the usual paradigm is that more complex approaches are bound to produce more reliable predictions. This actually was the purpose of a comparison I conducted using three C-N models of increasing complexity (38) : SUNDIAL (Bradbury et al., 1993), CERES (Jones and Kiniry, 1986), and DAISY (Hansen et al., 1993). The models were run on the Châlons "ecobalance" experiment (described in section 2.4), using various parameterisation scenarios involving either coarse of detailed information on soil functioning, and some degree of model calibration or none. None of the models clearly outranked the others, but each of them proved best for the simulation of a particular component : heat and mass transfer in soil for DAISY, crop growth and N uptake for CERES, or N mineralisation for SUNDIAL. Regarding the critical issue of model parameterisation, SUNDIAL proved easiest to parameterise and fairly accurate, despite some of its components being rather simplistic. CERES appeared as a good compromise as regards parameterisation, operation, and accuracy, while DAISY presented the best potential for simulating the actual C-N dynamics, but at the cost of providing site-specific estimates for parameters such as hydraulic conductivity.

Although such global comparisons provided hints at the strengths and weaknesses of the various models, they do not really allow conclusions to be drawn as to the goodness of individual model components. Each model actually features its own combination of components and underlying approaches, for basic processes such as water movement in soil or evaporation calculations (Diekkrüger et al., 1995), which then interact strongly in producing the outputs for which the models are tested. This means that such comparisons hardly fit in with the usual paradigm of process-based modelling, which postulates that the model should be based and verified at the level of individual processes, the

[3]module refers to a particular component of the model, for instance water balance

level at which knowledge and data are available (Boote et al., 1996).

As a result, comparison of models at the module level should be advocated, with the following objectives :

i to gain insight on the goodness of process approaches based on various scales (*eg.* organ *vs.* plant or plant community) or concepts (Radiation Use Efficiency vs. biochemical cycle for net photosynthesis).

ii within models that use similar concepts, to decide which implementation is best suited. Implementation meaning that various methods are employed to solve equations (*e.g.* implicit or explicit numerical schemes to solve Darcy's law flow equations) or calculate input variables (*e.g.* single- vs. multi-layered canopies to compute light interception).

For adequate comparison, we thus need to be able to isolate the effect of the approach taken with respect to one individual process within the modelling structure - thus strong modularity in model design is required. Further, the outcome of the various approaches needs to be tested in a wide range of conditions (in terms of environment, system management, and time-frame). When analytical solutions are available, they allow a formal comparison over a continuous range of parameters relating to those conditions (6; Russo et al., 1989). However, in that case it is difficult to integrate observed data in the comparison.

The following paragraph summarizes a module-based comparison I conducted recently (12), focusing on the the soil carbon and nitrogen turnover module of four soil-crop models (CERES, NCSOIL, SUNDIAL, and STICS). The C-N modules of NCSOIL, SUNDIAL and STICS were extracted and linked within a common soil crop simulation shell adapted from CERES. Thus, they were all supplied with the same physical and chemical input data and differences in the outputs of the four resulting models could be directly ascribed to their C-N component. Their performance was assessed according to three criteria : short-term response to climate and crop residues input (in terms of N immobilization), annual basal soil net mineralization, and long-term dynamics of soil organic matter. The models were thus run on data sets involving net mineralization and topsoil inorganic N dynamics under contrasting bare or wheat-cropped soils, and long-term soil carbon data.

On a yearly basis, NCSOIL over-estimated the immobilization of inorganic N associated with the

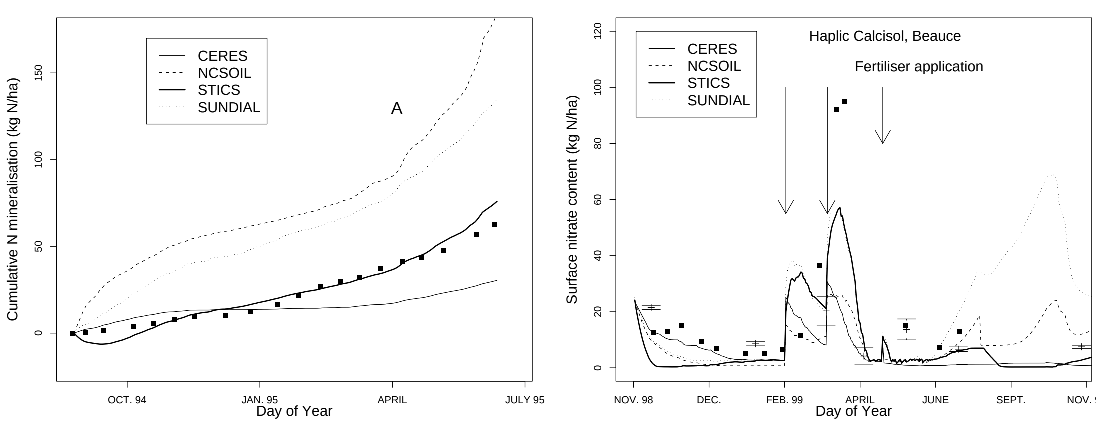


FIG. 2.4 – Simulated (lines) and observed (symbols) time course of net mineralization in Rafidin (A) and surface (0-20 cm) soil nitrate content in on location of the Beauce experiment.

decomposition of crop residues, and CERES predicted extremely low mineralization fluxes (Figure 2.4). Re-calibration of the latter model was unsuccessful over the range of conditions tested, probably because CERES does not simulate the microbial biomass compartment - contrary to the other three modules. Note that this flaw had prompted me early on to switch to the more mechanistic model NC-SOIL, as explained in the next section (2.3.3). The results with the long-term experiment revealed a trade-off between N and C simulations (Figure 2.5). The models that emerged as more realistic in the prediction of topsoil N dynamics (SUNDIAL and STICS) simulated the most drastic decrease in soil organic matter (SOM) at Broadbalk (UK). Comparison with a dedicated SOM model, RothC (Jenkinson et al., 1987), lead us to hypothesize that the discrepancies resulted from the plant module of CERES strongly under-estimating crop residue return to soil, and most notably through rhizo-deposits and root biomass. This implies some recalibration of parameters such as the radiation use efficiency (to increase primary net production), and should also affect the N balance of the system, since extra biomass production requires extra N. I have not investigated this issue yet, nor seen any work along that line - although the problem was also mentioned with the soil-crop model MAGEC (Smith, 2001).

The practical conclusion of model- or module-based comparison exercises should be some guidance

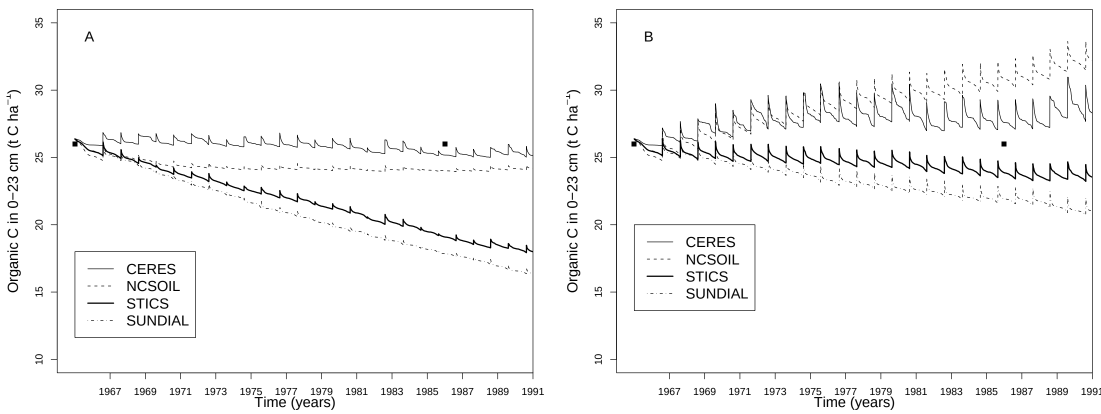


FIG. 2.5 – Simulated (lines) and observed (symbols) time course of surface (0-23 cm) soil organic carbon under the unmanured continuous wheat at Broadbalk, using two carbon return values : those simulated by the plant component of CERES (A), and a fixed amount of 1.3 tons C ha^{-1}, as estimated with the carbon model RothC (B).

in selecting the approach most suited to one's particular needs. However, the results are often not so clear-cut as to make this choice obvious. In the above example, it is obvious that the original CERES C-N module should be rejected, in favour of any of the other three models. This warrants changes in the structure of the CERES model, a task I have been involved rather frequently with, and which is the subject of the next section. However, coming back to the example at hand, the picture with the other three C-N modules is rather blurred. By default it may mean that they all perform equally well (or badly !), so that they may be used until further comparison work turns more clearly in favour of one particular module. One may also argue that each model has a domain in which it performs better than the others. For instance, the fact that STICS was built from data including calcareous soils gives it an advantage in the simulation of the rendzina soil with high $CaCO_3$ content (Figure 2.4). However, precisely delineating this domain is a daunting exercise, since it would imply testing the models in dozens of sets of conditions. An intermediate approach, which has already been suggested in the atmospheric sciences community, would consist in combining models to reduce the prediction uncertainty inherent to reliance on a single model (Fisher et al., 2002).

2.3.3 Improvement of model component

When I started with CERES in the early 1990's, most of the work on this particular model had been focused on predicting crop yields as a response to management and pedo-climatic conditions, with environmental assessment lying somewhat beyond scope. The emphasis was thus placed on crop components, although some processes and environmental outputs were already present, such as nitrate leaching, denitrification, or soil carbon balance. Compared to the agronomy-orientated type of work, there had been little verification of the model's performance regarding those components - none of which was done in France or Western Europe (Quemada and Cabrera, 1995; Bowen et al., 1993; Comerma et al., 1985). I therefore started working along that line, testing and tentatively improving the modules of CERES that appeared critical for environmental purposes : soil water balance (1), soil C-N dynamics and nitrate transport (2). These aspects involved specific, detailed testing and publication, as exemplified in the inset on the next page for the first one (water balance). For other processes, including soil heat balance and soil denitrification, I took advantage of previous work (Hoffmann et al., 1993; Hénault, 1993), considering these modifications had already been validated and published independently. They were tested later on at the outcome of the "ecobalance" experiment, which provided us with a comprehensive data set on the cycles of water, C and N in an oilseed rape field (see section 2.4).

Ideally, the publication of modifications to a model leading to improved performance, at least under a particular set of environmental conditions, should lead to a wider adoption in the community of modellers. In the case of CERES, although we had some contacts with the groups in charge of its development (J. Ritchie of Michigan State University, and G. Hoogenboom of the University of Georgia), we never went so far as exchange pieces of model source code to implement some of our modifications into the DSSAT shell that serves as a front-end to CERES world-wide. Our contribution thus passed through the usual 'literal' means, via the concepts and parameterizations proposed in the papers we published. It is reassuring, however, to see that later work was done along similar lines as ours, in Australia and America, for water balance and soil C-N dynamics (Gijsman et al., 2002; Asseng et al., 1998; Gerakis and Ritchie, 1998). Also, some of the concepts in the CERES-Rapeseed model were taken up by the APSIM group in Australia to set up their 'canola' model (Farre et al., 2002), along with some of our data to test it.

The fact that innovations diffuse slowly, in comparison to the abundant literature devoted to model improvement, raises the issue of mutualisation and capitalisation. How can models build on the vast feedback they generate after being released to the scientific community ? Should model development be centralized in a particular group, or open to any volunteers, just like the open-source computer freeware projects ? Sharing the development of models among various groups specialising in particular components (or modules) appears as the way of the future to improve the efficiency of this process. Initiatives at the INRA or European level were recently taken to provide the necessary scientific and information technology framework, making it possible to build models as a combination of individual bricks, and to tailor them to the particular needs of the users (eg, the SEAMLESS Integrated Project). The assumption here is that any model component may be seamlessly plugged in and out of a common shell, and that it will perform independently of the other components. This modularity principle is a rather bold tenet, but it is indispensable to practically envisage shared improvement of models over time. I am not aware of published proof of concept for modularity, although such work could be considered. For instance, with the module-based comparison of section 2.3.2, it would consist in calibrating the various ecosystem models used (STICS and SUNDIAL) on variables other than those pertaining to the soil C-N module (soil water content, crop biomass and N accumulation), and comparing the latter outputs with those produced based on the common CERES shell.

Improving the simulation of water balance

The original water balance of CERES was tested against field data collected from various pedo-climatic sites in France (1). Process-oriented analysis of the results showed that the cascading, tipping-bucket scheme used for computing downward infiltration lead to a systematic under-estimation of soil water content in fine-textured soils (Figure 2.6). This prompted introduction of Darcy's law in the drainage and capillary rise parts of the model, resulting in a more accurate prediction of soil water content. For a 1-year period, the root mean square error between modelled and measured soil water storage was in the range 1 to 1.7 cm water for the original model, in contrast with 2 to 6.8 cm with the original model.
I later on conducted a theoretical appraisal of a generic capacity model like CERES by comparing its predictions with an analytical solution of Richards' equation. Interestingly, the comparison showed that the choice of the Darcy-type infiltration equation that I implemented in CERES lead to results similar to those of the exact analytical solution of the Richards equation (6). It thus provided a theoretical validation of the new water infiltration scheme a posteriori.

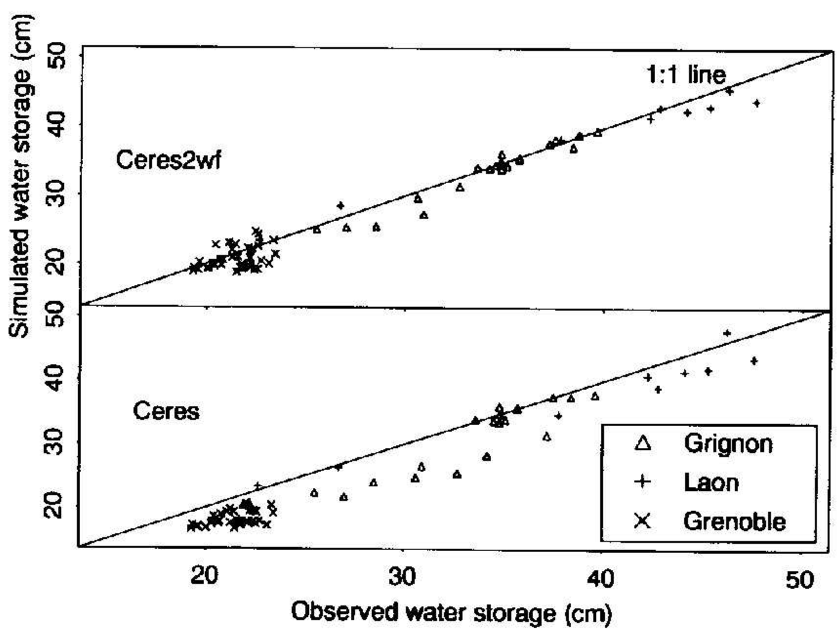


FIG. 2.6 – Comparison between simulated and observed soil water storage (0-120 cm) at three sites in France, using the original (Ceres) and modified (Ceres2wf) models (from (1)).

2.3.4 Development of new model component

As mentioned in the above paragraph, some of the processes relevant to environmental assessment were not present within CERES when I started working on it, a trait pertaining to all crop models. The missing modules included gaseous emissions of nitrous oxide (N_2O), ammonia (NH_3), and nitrogen oxides (NO_x). Some crop species were also unavailable, among which the most notable in our case was oilseed rape since it is the crop we used in the "ecobalance" experiment (see section 2.4). Lastly, the fate of pesticides was not taken into account, although a version was developed later to simulate atrazine (Gerakis and Ritchie, 1998). Regarding the latter point, I chose not to build on the CERES basis since it was no longer maintained, and had only been tested on a single experiment in the US. There were on the other hand a host of 'pesticide fate' models available, with a worldwide support from various research groups, the only drawback being that these models were focused on soil processes (especially vertical transport) rather than on plant components. In particular, none of these models is meant to predict the impact of a given pest control strategy on plant growth and final yield. Including such capacity in one of these models is therefore a prerequisite for environmental balance purposes, although it remains a medium-term for me. Direct coupling of one of these pesticide fate models with CERES proved rather difficult, since the former involves time steps and vertical discretization much finer thant the latter - owing to the fact that pesticides are transported much slower and over smaller distances than mobile solutes like nitrate. As a result, the source code of pesticide models is too complex and intricate to allow easy modification. So far I have simply selected a particular model, the Pesticide Root Zone Model, PRZM (Carsel et al., 1985), from the US Environment Protection Agency - a model widely used including for homologation purposes (FOCUS, 2000), and used it 'as is' to simulate the fate of various herbicides, together with a graduate student, Laure Mamy (see section 2.6.3). However, in a near future I plan on contributing to improve the simulation of pesticide stabilisation via the formation of non-extractable residues, together with my colleague Enrique Barriuso, as the outcome of the work of a graduate student, Macaire Edzangongo. Also, preliminary tests of the volatilization routine of PRZM, in collaboration with Carole Bedos (INRA Grignon), showed that it should be upgraded by making use of a physically-based description of atmospheric diffusion (87).

To summarize, my past work on the integration of new modules has thus essentially involved the CERES model, and was focused on adaptation to oilseed rape and the integration of gaseous emissions. It generally involved close collaboration with colleagues from my laboratory or INRA specialized in the processes at hand, upon joint research projects. The new modules included :

- growth and development of winter oilseed rape, with the contribution of crop ecophysiologist Pascal Denoroy (INRA Bordeaux) ;
- ammonia volatilization, based on the module that Pierre Cellier and Sophie Genérmont (INRA Grignon) orginially developed from their mechanistic model for the STICS model (Génermont and Cellier, 1997).
- the emissions of nitrous oxide, via the denitrification and nitrification pathways, based on the NOE algorithm developed by Catherine Hénault (INRA Dijon - (16)) ;
- the emissions of nitrogen oxides (NO_x), also via denitrification and nitrification, and based on the work by Patricia Laville (INRA Grignon) and Catherine Hénault (17).

Besides making the necessary adaptations to the original modules so that their time and spatial scales be compatible with CERES, my own contribution in the integration also involved some discussion with the 'process specialists' in the design of the modules themselves. For instance, together with a graduate student, we found it necessary with the NO_x module to change the shape of the response curve of nitrification to soil water content, so that nitrification would decrease above the field-capacity water content, as is usually observed (Cortinovis, 2004). In the case of winter oilseed rape, I started building on an existing model, only to find out most of its modules had to be revised because of their empirical basis. So I essentially re-constructed the various crop components (leaf and root elongation, net photosynthesis, water and nitrogen stress functions) from scratch, based on the data available at that time on crop ecophysiology. This involved significant efforts during and in the aftermath of the 'ecobalance' experiment to collect, analyse, and model field data, as well as publication (3; 4; 8; 22; 41; 42). This is illustrated below in the case of leaf senescence. The model was subsequently maintained and improved by Romain Roche (INRA, Grignon).

Testing the resulting model against field measurements made up a major part of my work. The state of progress in this respect varies across the above-mentioned components. The CERES-Rapeseed model was tested in under a range of conditions in France, Germany, Denmark and the UK (13). Testing is also advanced for N_2O, which has correctly compared with field emission data from three contrasting soils in the Beauce area, southwest of Paris (21) - as detailed below. The NO_x module originally developed by C. Hénault from laboratory incubation studies (Garrido et al., 2002), was first directly inserted in CERES by Jérôme Cortinovis, a graduate student at the University of Toulouse who worked under my supervision for a few months on the prediction of NO_x emissions with a crop model (Cortinovis, 2004). However, some of the laboratory-estimated parameters of this module had to be calibrated to provide correct predictions of NO_x dynamics. The module and its parameterisation was thus revised according to the field data collected in Grignon, first in a stand-alone (module) mode (17). Inclusion of these modifications in CERES by a graduate student, Marie-Noëlle Rolland, improved the simulation of NO_x emissions, althouhg it the implementation of a thin layer at the soil surface was required to correctly predict the dynamics of fertilizer incorporation into the soil and subsequent nitrification. This work is currently on-going as part of Marie-Noëlle Rolland's Ph.D. programme, under my supervision. Lastly, the ammonia volatilization module was only tested once, against measurements made with static chambers in Southern Italy (70). More detailed testing and sensitivity analysis are currently carried out as part of a joint research project with colleagues from the UK.

2.4 From model to experiments, the perpetual swing

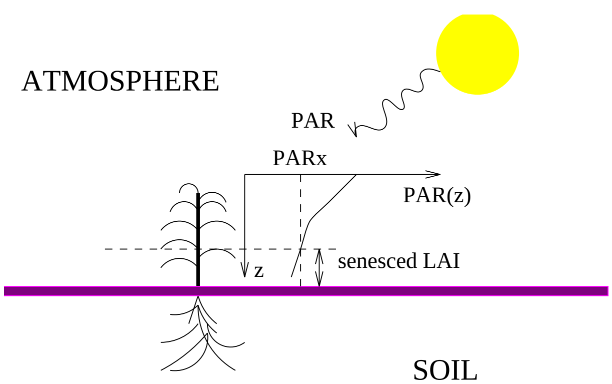
Experimental data are central to any modelling pursuit, whether in the stage of module design, integration into an ecosystem model, detailed model testing, or extrapolation to larger scales. Experiments are usually designed prior to running the model, which is then tested a posteriori once the experiment is over. However, experimental design might be improved by prior model runs to identify the sampling dates or type of variables which provide the most useful information. For instance, we ran the PRZM model to select the dates at which soil should be sampled to monitor the dynamics of a set of herbicides characterized by a range of persistence characteristics and application timings (88). In terms of variables monitored, dealing with environmental outputs implies a lot more efforts than with the agronomic outputs ordinarily used for crop models, at least in the detailed testing phase. Besides monitoring the dynamics of crop biomass, leaf area index and N content, along with soil water and N status, it is necessary to measure the losses of N or pesticides, whether gaseous or leaching. Gaining such level of insight into the processes going on in the field is indeed necessary to separately test the various components of the environmental balance model. This warrants specific and comprehensive experiments of which I initiated two : one on the N budget of a winter oilseed rape crop, detailed below, and another on the fate of trifluralin, an herbicide used on oilseed rape (19). Since the goal of this assessment is to improve the system's environmental performance, these experiments should also include variants in terms of management practices. For instance, the "ecobalance" experiment involved three fertilizer N treatments for the oilseed rape, and also the effect of cover crops

Development of a module for leaf senescence

The development of the CERES-Rapeseed model provided me with the opportunity to test a new approach to leaf senescence, including the effect of shading due to competition for light in the canopy. This followed the scheme first suggested by Ghislain Gosse (INRA) for alfalfa (Derache and Guen, 1986). According to this scheme, shading-induced leaf senescence occurs at the bottom of the canopy if the transmitted radiation drops beneath a given threshold (Fig. 2.7). This threshold level of radiation (noted PAR$_x$) corresponds to an equilibrium in the plants' carbon budget where gross photosynthesis exactly compensates for losses by respiration.
For a given of incoming incoming photosynthetically active radiation (PAR), PAR$_x$ may be translated into the maximum leaf area (LAI$_x$) that can be maintained, by inverting the classical Beer's law of radiation attenuation inside the crop canopy. The equation reads :

$$\begin{aligned} LAI_x &= 1/k \log\left[PAR/(PAR_x f_T)\right] \text{ if } PAR \geq PAR_x f_T \\ LAI_x &= 0 \text{ otherwise} \end{aligned} \tag{2.1}$$

Since crop respiration is affected by temperature, PAR_x is multiplied by a temperature factor f_T involving an Arrhenius law with a Q_{10} of 2 and an optimum at 20°C. PAR$_x$ was calibrated at 0.2 MJ m^{-2} PAR d^{-1} against data of total and actual LAI for the treatment with ample N fertilization in the 'ecobalance' experiment, which gave good results in the other treatments and test sites (Figure 2.7).



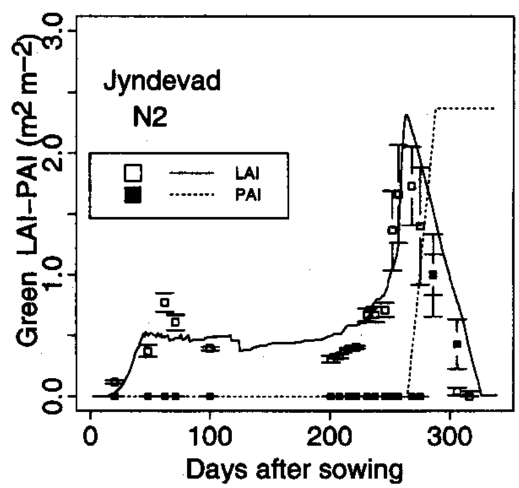


FIG. 2.7 – Modelling of leaf senescence induced by shading. Senescence sets on for the bottom layers of leaves that receive a transmitted radiation inferior the PAR$_x$ threshold (LEFT). Simulated (lines) and observed (symbols, ± s.d.) green LAI and PAI (pod area index) in Jyndevad (DK), on an independent data set (RIGHT). From (4).

(mustard or rapeseed volunteers) in the cropping sequence. The resulting comparison of N emissions across the fertilizer treatments was shown earlier on Figure 2.1. The trifluralin experiment showed that incorporating the herbicide into the soil surface layer had a drastic effect on volatilization, abating the flux by several orders of magnitude. Simulation of a nearly immediate incorporation showed that it stopped volatilization while not increasing the leaching losses, leading to an overall benefit in the environmental balance (87).

Such detailed experiments are highly resource-consuming, and so may only be conducted in a few

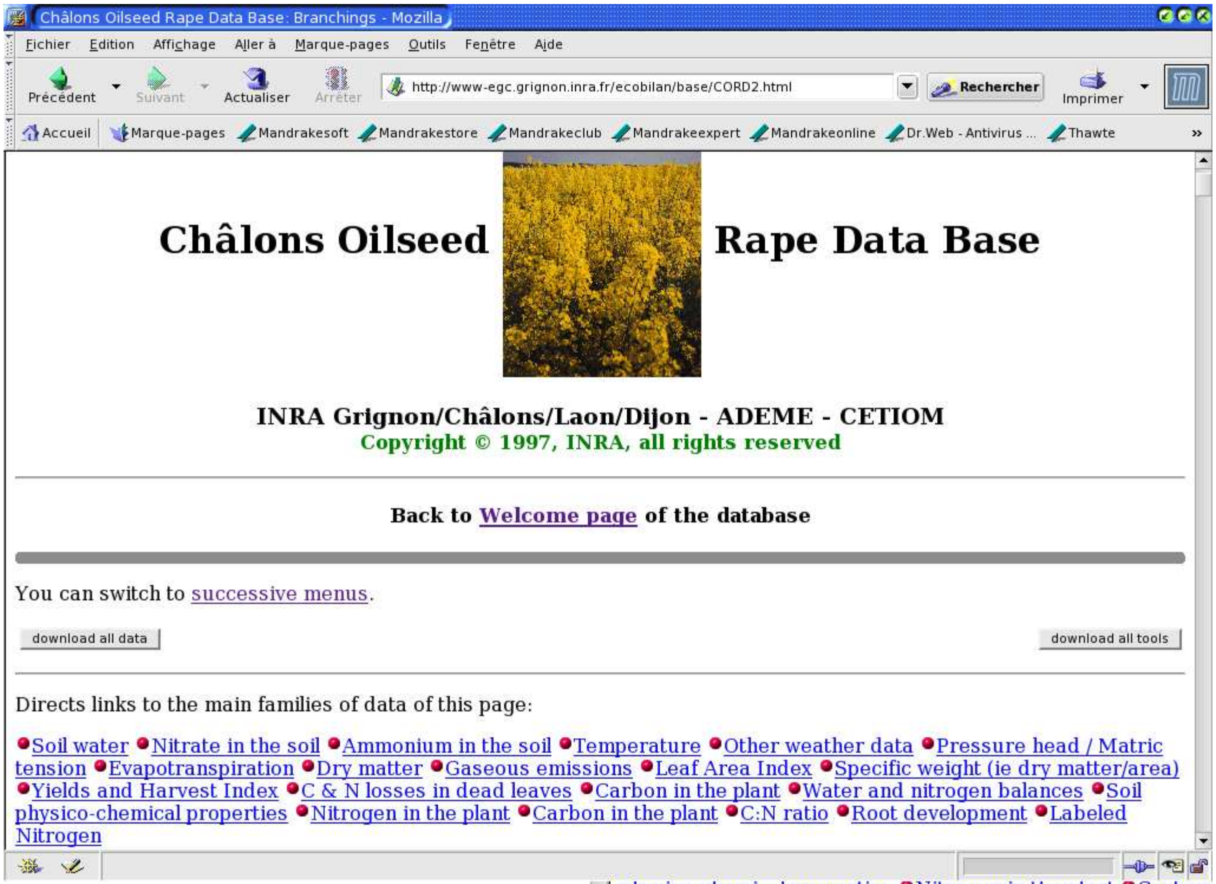


FIG. 2.8 – Screen shot of the “ecobalance data base” server, showing the type of data available. “Ecobalance” was a comprehensive experiment on water, C and N cycling in an oilseed rape-cropped field in Northeastern France. It was coordinated by Ghislain Gosse (INRA), and involved four INRA laboratories specialised in the various aspects of the cycles considered (7). After publication, the data were organized into a data base for which an HTML-based interface was developed, and made accessible through the Internet on a dedicated Web site.

instances. Actually, I am only aware of a few similar examples for N, and none for pesticides. It is probably because scientists are often focusing on the particular category of processes or type of environmental impacts relevant to their research field. Also, analysing and organizing large data sets for modelling purposes is a serious task which probably deterred some experimentalists. There are probably many more data sets in the scientists’ computer files (including mine) than there actually is in the published literature ! Sharing data sets has been a long standing issue in modelling, periodically spawning dreams that modellers would manage to make their data sets accessible to the scientific community and thereby mutualize the burden of model testing. In reality, only few such ’meta’-data bases of publicly-available data sets were ever set up. One example is that distributed by the ICASA network, based on a data base format (Hunt and Boote, 1998) compatible with the DSSAT software package (under which CERES is currently distributed). Such efforts should definitely be fostered, and are immensely valuable. For instance, the "ecobalance" data set we published on the Web (Figure 2.8) was later used by other scientists for such diverse purposes as the modelling of nitrate transport systems in roots (Malagoli et al., 2004) or the calibration of the APSIM and SIRIUS oilseed rape models. The barriers to sharing data sets include first the resources required to organize and convert one's own data set into a more broadly-usable format such as that of ICASA, implying the inclusion of meta-data to qualify the data themselves. There are also issues dealing with intellectual property and recognition of work done by the scientists who spent a lot of efforts collecting the data. Although contributing a data set is a potentially most valuable addition to current science, it is not easy to publish *per se*.

Potential use of isotope tracers

The use of labelled inputs offers a powerful means of tracking their fate in the soil-crop systems, and approaching the environmental balance. The resulting data also provide a more stringent test than total inorganic N data in the test of N models - provided that the models have the capacity of simulating the introduction of compounds with labelled N or C (Bradbury et al., 1993). Such is not the case for the majority of soil-crop models, with the exception of SUNDIAL, which I could test against data collected in a set of experiments involving winter wheat and oilseed rape crops and various sources and application dates of mineral fertiliser N (10). The comparison of observed and simulated dynamics of fertiliser-derived N evidenced intrinsic problems with SUNDIAL in the simulation of autumn immobilisation of soil nitrogen as well as spring offtake by the oilseed rape crop. Such level of details in the process analysis of model performance could only be achieved by the use of tracer data. Some discrepancies were also noted with the simulation of ammonia volatilization, but this could be detected only because direct measurements of unlabelled ammonia volatilization were available (Recous et al., 1988). It is indeed only recently that gaseous emissions could be quantified for labelled N, because of the high background concentration of N_2 (Mathieu et al., 2004). Also, this technique is restricted to micro-plot scale in the field, and there is usually a missing term in the labelled N budget. In the case of pesticides, these methods are further restricted to the laboratory because only radio-active isotopes are available. Isotopic tracing techniques are probably limited to the investigation of processes on scales ranging from soil microcosms to micro-plots in the field - with the exception of natural abundance-based methods, such as the use of ^{13}C, which can be used at the ecosystem level to test soil organic matter models (Balesdent, 1996).

Extrapolating a model across a range of physical and agronomical conditions, as detailed in the next section, requires another type of experiments, where the emphasis is put on the combination of 'factors' sampled rather than on the number of state variables monitored in one location. Physical conditions may be sampled on the basis of soil types, climatic zones, and their expected influence on the workings of the soil-crop system. Crop management is connected to some extent to these factors, but may be also tested as an independent factor over a range of physical conditions. Network-type experiments involving a host of geographical sites selected using the above criteria and managed along similar guidelines offer a prime basis for such extrapolation work. European Union-funded research provided unique opportunities for deploying such networks, primarily for crop production purposes, and later on for environmental-orientated research. I was for instance involved in the last of a series of EU projects on sorghum production and environmental impacts in the Mediterranean area, funded under the fourth and fifth framework programme (70). Although these projects involved as far as a dozen of geographical sites, modelling could only be done for a restricted subset of those sites, because of gaps in the data collected. This was especially true for the 'environmentally-orientated' sites, since the modelling of the N cycles could only be done in 2 out of the 6 sites planned initially (70). The reasons for this included faulty weather data, the failure of site managers to report on particular aspects of the experiment (management data, soil characteristics, crop growth data, etc...), and generally a lack of response from project partners. This emphasizes the limits of a 'centralized' organization where experiments are conducted by a set of site managers, and modelling is done by a separate group of modellers. In the sorghum network, the one site where modelling was done over the whole range of data available actually involved the partner using the model themselves. In particular, a Ph. D. student used the model in her dissertation, under my supervision (Mantineo, 2000). Getting the scientists who collected the data for their own purposes in the modelling process is thus a key issue in achieving a proper use of models and data, and mutual benefits for both parties. I was therefore very happy to take the opportunity of collaborating with various researchers across Europe (in Germany, Denmark, Spain, the UK and Italy), as well as from other parts of the world (including the USA and the Réunion island) to build my own network of sites for model extrapolation (13) - see Figure 2.9.

Another option to take advantage of network-type experiments is to get involved in the experiments themselves (which is also a good way to keep one's hands on the real-life going on in the field). This lead me to participate in a project funded by several French Ministries (74), in which three sites in the Beauce region (central France) were monitored for N_2O emissions. My particular contribution consisted in taking wheat plants and soil samples every one or two months to be able to verify the N balance and crop growth components of CERES (12).

As a conclusion, the collection of data is central to any modelling project, and both components should be designed in tight connection. There is clear trend in recent research projects to integrate modelling in the early phases of the research plan, and not as a possible add-on in the last year of the project (as was the case with the sorghum network for instance). Using models to design experiments before they are actually implemented, and then insuring a rapid feedback from modelled data to field data as the experiment goes on is a key to better success in combining both sources of knowledge to improve our understanding of the system at hand. The involvement of 'experimentalists' in the modelling efforts, and vice-versa, is probably the best way of integrating the two sides of the problem. This implies efforts on the modellers' part to transfer their skills and tools, and also to save some time for experimenting... which is getting harder and harder for me, I am afraid !

2.5 Model extrapolation over time and space

Testing and fine-tuning a model based on experimental data from one's favorite field research site is an exercise at which modellers generally excel, producing miraculous fits between observed and model-predicted data. Far less clear is the ability of these particular models to simulate situations involving entirely new sets of soil, climate or cropping conditions, with much less information available to parameterize or verify the model. Testing the model in this larger-scale extrapolation phase is a cumbersome task because it implies the definition of a standardized methodology to estimate model inputs, and the collection of a series of data sets encompassing a range of physical and technical conditions. This is probably why this step is often skipped by modellers, who go directly from detailed model testing in a single site to application over a host of scenarios. I found evidence of this by analyzing the literature on modelling (Figure 2.10), which had lead me to mention extrapolation as the 'missing link' in the overall chain from model development to practical applications (13).

Anticipating this problem during my Ph.D., I had suggested taking into account the level of information available to parameterize the models when testing them. As an example, Figure 2.11 depicts the variations of the root mean squared errors (RMSE) of three models (CERES, DAISY, and SUN-

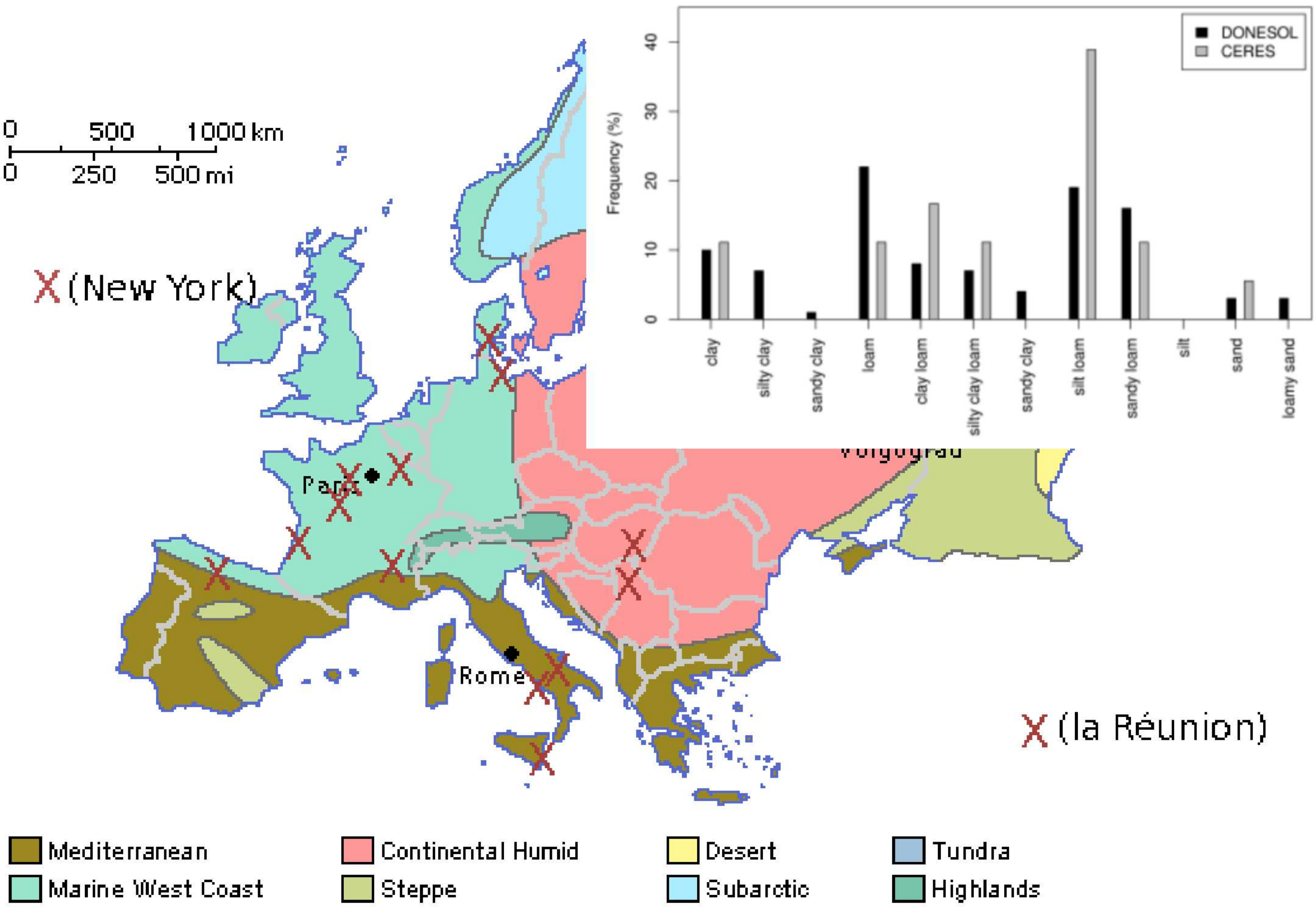


FIG. 2.9 – Geographical locations of sites in which our version of CERES was tested, showing their climatic situations. Inset : distribution of texture classes among the soils tested (N=19) compared with that of the DONESOL data base covering the arable soils in France (Bastet et al., 1998).

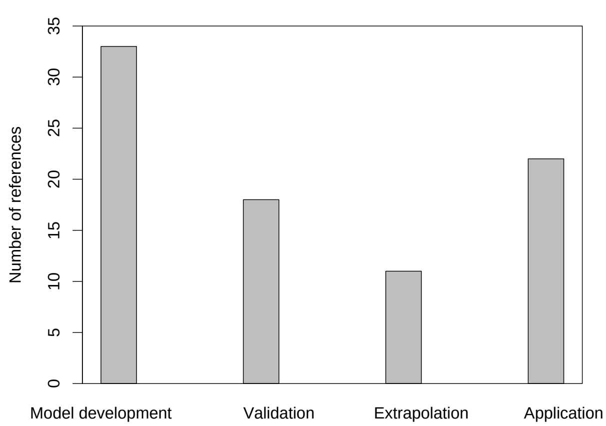


FIG. 2.10 – Number of references cited in the CAB data base (1997 to 2000) including the keywords CROP and MODEL, broken down into the various modelling phases of Figure 2.3.

DIAL) in the prediction of three selected variables, for two extreme parameterisation scenarios in the "ecobalance" experiment. The 'baseline' scenario corresponds to an extrapolation phase, whereas the 'optimum' scenario uses more detailed information on soil properties, and some parameters are even fitted against measured data (38). Surprisingly, most models performed significantly better for the

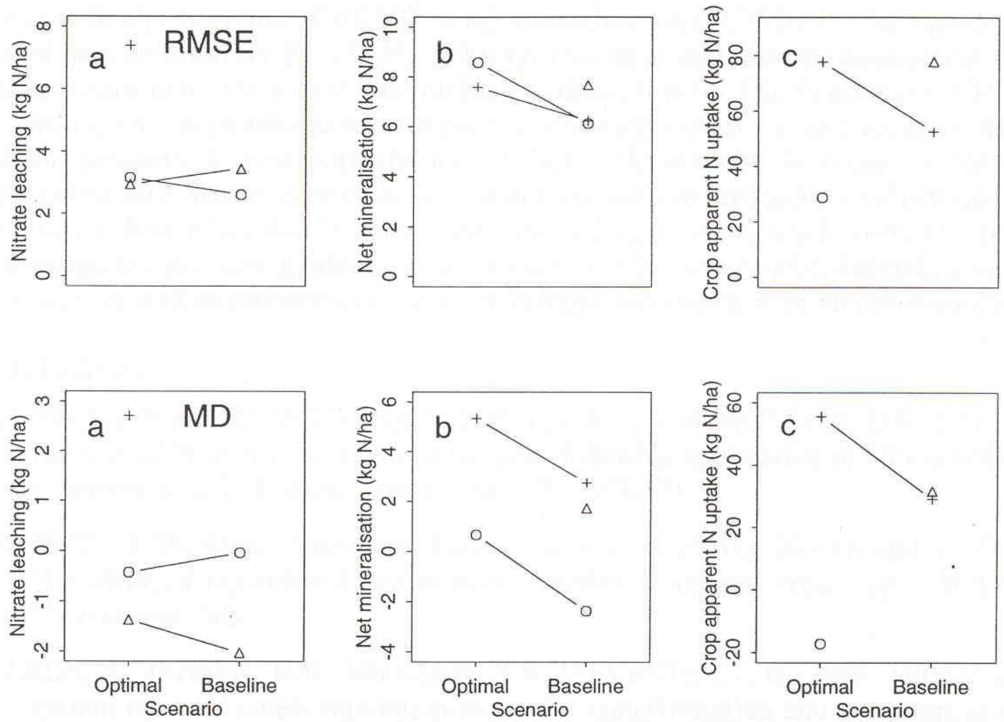


FIG. 2.11 – RMSEs (upper graphs) and Mean Deviations (lower graphs) of the CERES (○), DAISY (△) and SUNDIAL (+) models, for the the baseline and optimal parameterisation scenarios and three variables : **(a)** the bimonthly NO_3^- leaching flux (bare soil) **(b)** the bimonthly net mineralization flux (bare soil) **(c)** the apparent crop N uptake (oilseed rape). From (38)

baseline scenario, except for leaching with DAISY's goodness of fit improving when using measured hydrodynamic parameters instead of texture-derived estimates. DAISY appeared to have the best potential for simulating the actual C-N dynamics, but this came at the cost of providing site-specific estimates for parameters such as hydraulic conductivity. On the other hand, CERES struck a good compromise between parameterisation costs and accuracy, especially in the perspective of extrapolation to wider set of physical conditions.

I later extended the definition of the 'baseline' parameterisation scenario to define a standard methodology to estimate the soil parameters of CERES *a priori*. This procedure converts routinely-available soil properties (particle-size distribution, gravel content, bulk density, total soil carbon and nitrogen content) into functional characteristics involved in the simulation of water movement and soil biological transformations. It involves several pedo-transfer functions (Jones and Kiniry, 1986; Suleiman and Ritchie, 2001; Driessen, 1986) for the parameterisation of water balance, which were selected from a larger set (Acutis and Donatelli, 2003) using soil nitrate data from a network of 36 field trials in France (Dejoux et al., 2003). Regarding the turnover of soil organic matter, we used a simple partitioning based on the history of organic amendments in the field considered (Houot et al., 1989). More information on the parameters and their calculation may be found on the Internet at *http ://www-egc.grignon.inra.fr/ecobilan/cerca/intjavae.htm*, where the estimation procedure has been implemented within an on-line front-end.

The procedure was tested in fuller details on a network of five locations across Europe, involving a range of climate, crop and soil types (13). As could be expected, significant deviations between ob-

TAB. 2.2 – Calibrated parameters for the various experiments simulated with CERES.

Location of Experiment	Parameters name	Unit	Fitting variable	Associated routines
Kiel (GER)	Field-capacity	$cm^3\ cm^{-3}$	Soil water profile	Water balance
Rafidin (FR)	Field-capacity	$cm^3\ cm^{-3}$	Soil water profile	Water balance
	Initial size of microbial biomass	mg C kg^{-1} soil	Topsoil nitrate	Turnover of SOM
Villamblain (FR)	Field-capacity	$cm^3\ cm^{-3}$	Soil water profile	Water balance
	Sensitivity to cold temperatures	Unitless	Crop dry matter	Crop phenology
Barrafranca (IT)	Sensitivity of root extraction of N to water stress	Unitless	Crop N content	Crop N uptake
Candasnos (SP)	Initial size of microbial biomass	mg C kg^{-1} soil	Topsoil nitrate	Turnover of SOM

servations and model outputs were noted in all sites, and could be ascribed to various model routines (Table 2.2). In decreasing importance, these were : water balance, the turnover of soil organic matter, and crop N uptake. A better match to field observations could therefore be achieved by visually adjusting related parameters, such as soil water content at field-capacity or the size of soil microbial biomass. As a result of this calibration, model predictions fell within the experimental errors in all sites, and also within the range of published values for similar model tests. The proposed *a priori* parameterisation method thus yields acceptable simulations with only a 50% probability, a figure which may be greatly increased through *a posteriori* calibration. Modellers should thus exercise caution when extrapolating their models to large sample of pedo-climatic conditions for which they have only limited information.

Bearing this limitation in mind, I went on to use a similar parameterisation to simulate wheat cropping systems at the regional scale in the greater Paris basin, in the framework of the N_2O project mentioned above (74). Elementary simulation units were defined by overlaying maps of soil types and land use. Weather data was taken for each unit from the closest station available, and 'average' crop management practices were defined based on a regional survey. Some of the soil parameters required by CERES were directly supplied by our colleagues specialized in soils data bases, using their own pedo-transfer functions (Bastet et al., 1998), or their own expertise. Extrapolation was done in three administrative agricultural sub-regions involving one test site each. We therefore could judge the performance of this spatial parameterisation procedure in those sites. Surprisingly, there were little differences between these simulations and those resulting from the local parameterisation, based on more detailed characterization of soil properties (*e.g.*, measurement of soil hydraulic conductivity - Figure 2.12). This highlights the benefits of using pedo-transfer functions obtained in the area of interest in the estimation of water retention parameters, as was the case here (Bastet et al., 1998). It should however be mentioned here that no such rules were available for the micro-biological parameters governing the production of denitrification- and nitrification-mediated N_2O. The parameter sets used in the spatial scenario of Figure 2.12 were thus the same as those of the local scenario, and obtained from site-specific measurements in the laboratory (16). Establishing relationships between those parameters and basic soil characteristics remains a challenge for future research on the prediction of N_2O emissions. Ecological studies at the level of microbial communities involved in the various transformations of N leading to N_2O production and reduction are expected to help in this pursuit, although it is a rather long-term prospect.

As an application of the above work, Figure 2.13 shows a map of N_2O emissions in the Beauce region

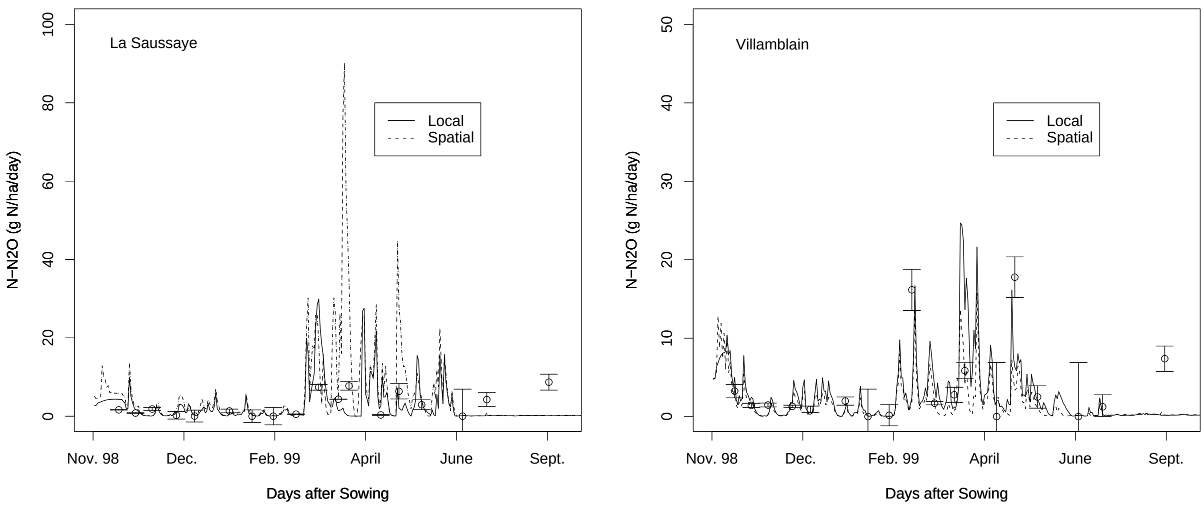


FIG. 2.12 – Simulated (lines) and observed (symbols) emissions of N_2O in two test sites in the Beauce region (an Haplic Luvisol in La Saussaye, and an Haplic Calcisol in Villamblain). In the local parameterisation scenario, detailed, site-specific information on soil properties was used, whereas the spatial scenario involved only information derived from soil maps.

obtained with CERES, for the 1997/1998 cropping season. The map emphasizes the magnitude of the variations across soil map units and sub-regions. The mean flux over the the three sub-regions of Figure 2.13 were compared with the estimates obtained using the IPCC methodology for inventorying N_2O emissions (IPCC, 1996). The CERES estimates were substantially lower than the IPCC ones, and the same went for the emission factors (74). Such differences were also noted in a similar comparison nationwide in China (Li et al., 2001). These results highlight the necessity of using process-based models, which fully account for local conditions, in inventorying trace-gas emissions.

Lastly, extrapolating **over time** appeared indispensable to tackle carry-over effects from one crop to the next, and also address the issue of emissions occurring during the time intervals between two crops. Assessing the environmental balance of a particular crop requires a capacity to track the emissions induced by its management, whether during the cropping season, in the time interval before the following crop is planted, or even after this proceeding crop started growing. There is thus clearly an allocation problem, amounting to to breaking down the emissions of a cropping system among the various individual crops it is made up of.

We had first opted to make any given crop responsible for the period of time going running from its planting to the planting of the following crop. However, because carry-over effects may take place over longer time periods, we finally decided that emissions should be averaged over a number a crop rotations, and then broken down into the various crops rotated. This prompted us to introduce break crops such as pea and sugar-beet, in addition to oilseed rape, in order to simulate the most common

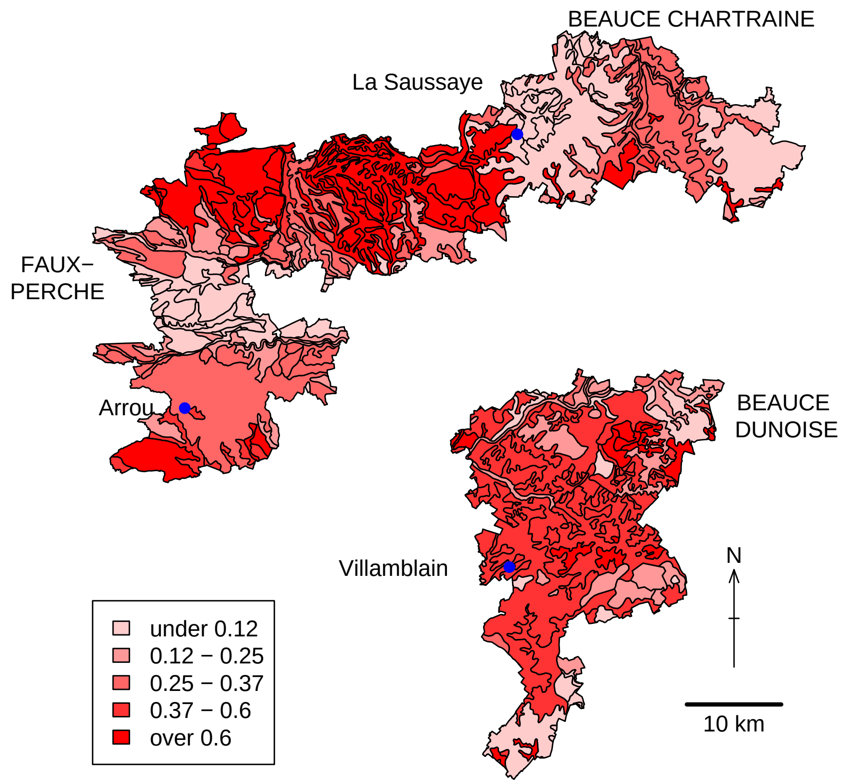


FIG. 2.13 – Simulation of N_2O emissions from wheat-cropped land in three agricultural sub-regions of the Beauce region (central France). The fluxes are expressed in kg N-N_2O ha^{-1}.

rotations in the Paris basin and other parts of Europe (26). For example, this capacity to simulate crop rotations enabled us to analyse the management of the interval between crop harvest and planting of the following crop, and to confirm experimental evidence that an early sowing of oilseed rape could reduce nitrate leaching in oilseed rape-winter wheat rotations (49). Running a seasonal crop model like CERES over time periods of more than thirty years revealed some possible drifts, most notably with the dynamics of soil organic matter, as was shown on Figure 2.5. However, the model did not go completely off course, as I had shown it to be the case earlier on with other models (39). This is probably due to the model being highly constrained and parameterized, preventing the occurrence of unlikely values of fluxes or state variables at any point in time. Figure 2.15 shows the simulation of a maize monoculture for various harvest regimes in the Miner (New York, USA) long-term experiment (Cardoso, 2000), and does not reveal any numerical divergence of simulated yields with time.

With respect to extrapolation over time, the challenge of giving accurate predictions of both short-term and long-term dynamics of C and N remains, and most likely requires adjustment of net primary production and the increase of photosynthates' partitioning to the roots. Currently on-going climate changes pose a second challenge, since they question the relevance of using historical series of wea-

Extrapolating from laboratory to field

Using parameter values obtained in the laboratory to simulate a field experiment is often cited as a risky endeavour. Laboratory-derived parameters may be flawed because obtained on disturbed soil samples, or under conditions that are remote from what actually occurs in the field. However, laboratory assays are often the only available method to parameterize soil biological functions such as soil organic matter mineralization, pesticide degradation, or trace-gas production. My experience in these matters is that the degradation of organic matter (whether fresh or endogenous to soil) could be approached reasonably well with laboratory incubations (2; 15). In the case of urban waste composts, we showed together with Sabine Houot (INRA Grignon) that an index derived from biochemical fractionation of organic matter could be used to parameterize the soil C-N module of CERES (14; 15). This conclusion, which applied in the laboratory as well as in the field (Figure 2.14), is an important result since it means a simple fractionation method could replace time-consuming laboratory incubations to characterize this type of organic matter.

Regarding other modules or models, we found together with Laure Mamy that degradation rates obtained in the laboratory for two of the three herbicides used in the field validation of the PRZM pesticide model had to be slightly adjusted (88). This somewhat mitigates the hypothesis that laboratory methods give a good proximate of field reality. Conversely, the NO emission module parameterized by C. Hénault from laboratory incubations of soil samples fertilized with mineral N failed to simulate the emissions observed in the field in Grignon (17). The module gave correct predictions after adjusting two of its parameters by a factor of 4, which is rather considerable (Cortinovis, 2004). The fact that laboratory parameters were unsuitable to the field situation probably was due to their having been obtained on disturbed soil samples, with NH_4^+ concentrations an order of magnitude higher than those usually occurring in the field.

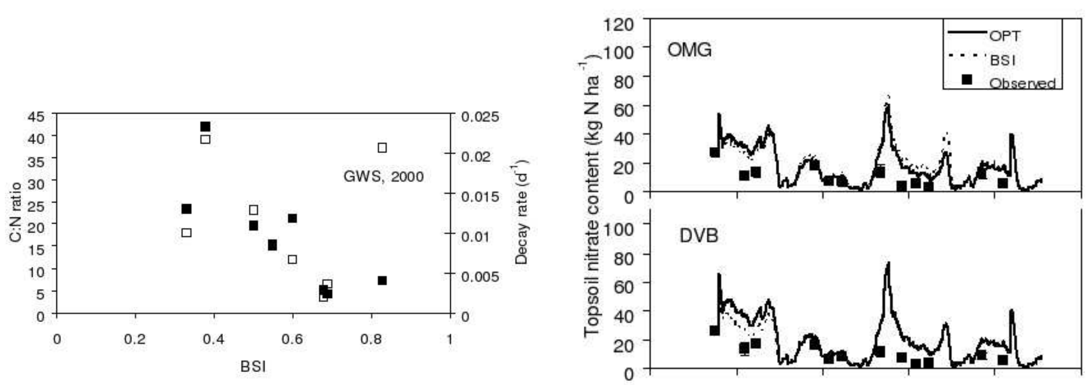


FIG. 2.14 – Use of a biochemical index (BSI) to parameterize the labile fraction of urban waste compost organic matter in CERES. The left-hand graph shows the relationship between BSI and the other parameters of the labile fraction : C :N ratio and degradation rate (R^2=0.66 for both relationships). The right-hand graph compares the simulations of topsoil nitrate content in the field experiment, obtained with the BSI-based (BSI) and optimum (OPT) parameter sets. From (14; 15)

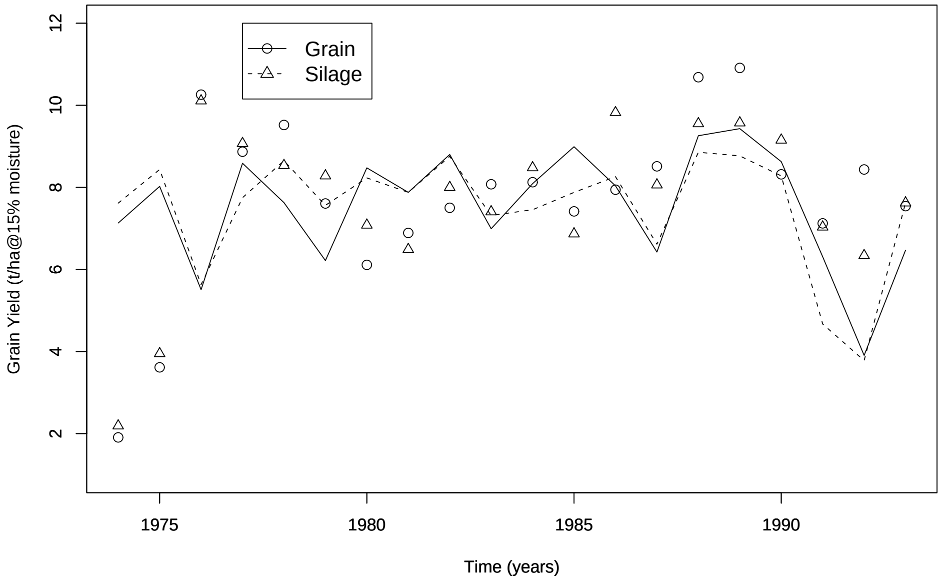


FIG. 2.15 – Simulated (lines) and observed (symbols) grain yields in the Miner (NY) long-term experiment. The experiment involves a maize monoculture with two harvest regimes : grain and silage maize. The simulation period runs from 1973 to 1992.

ther data (as I have exclusively done so far) to investigate long-term effects. Incorporation of data from general circulation models should definitely be sought, although it still raises compatibility issues in terms of spatial and temporal resolutions for use with crop models.

2.6 Application to life cycle assessment

As stated in introduction, the objective of the modelling work presented in the previous sections was to simulate fluxes and stocks of environmental interest as related to the management of arable fields, and more particularly the application of fertilizer N and pesticides. The general framework for the environmental assessment of those practices is life cycle assessment (LCA), a method which is based on fluxes of matter and energy from the particular production system at stake. The following subsections illustrate three production chains in which I combined field-scale modelling and LCA : biomass for energy, agricultural recycling of urban waste, and the introduction of genetically-modified, herbicide tolerant (GMHT) crops, In the first two examples, the framework of LCA appears particularly relevant since it makes it possible to compare the chains in questions with non-agricultural-based alternatives (fossil energy and land-filling or incineration of waste), for which LCAs are already available. The last example is agriculture-centered, but has the advantage of showing how a detailed method like LCA may complement other environmental assessment methods available for agricultural systems, such as the agri-environmental indicators (Girardin et al., 1999).

2.6.1 Straw for energy

The use of agricultural biomass for energy purposes increasingly appears as part of the solution to reduce global warming (Hall et al., 1991). The assessment of biomass for energy chains, whether for heating, transport or combined heat and power generation, was the background of the first examples of application of LCA to agricultural activities, and was actually the starting point of my work at INRA. Although the many reports available showed bioenergy had a high potential to offset CO_2 emissions from fossil energy consumption (Reinhardt, 2000; Ecobilan, 2002; Hartmann and Kaltschmitt, 1999), some controversy arose regarding the trade-off between the CO_2 savings and possibly large emissions of N_2O resulting from the fertilization of bioenergy crops. The LCA results of agrobiomass chains are very sensitive to the amount of N_2O emitted during the production of agrobiomass in the field, usually estimated with an emission factor that quantifies the fraction of applied fertilizer N that evolving as N_2O. However, this factor is highly variable depending on soil type, weather sequence, and crop management (Li et al., 2001). This emphasizes the need for process-based models which have the potential to produce estimates reflecting the conditions prevailing at the regional or local level. The following paragraph illustrates the use of such a model in the context of cereal straw, also tackling the issue of straw removal effects on cropping system variables. It results from a recent research joint project involving economists from INRA.

Crop residues have recently regained attention as a potentially considerable source of renewable energy. Available residues are estimated at 4.8 10^6 Mg worldwide, corresponding to an energy value of 70 10^{18} J ((Lal, 2005)). Among them, cereal residues are the largest source, making up two thirds of the total available amount. However, there is an on-going debate on the actual possibilities of straw removal (Wilhem et al., 2004). As reviewed by the latter authors, the experimental data currently available on the possible effects of straw removal on processes like soil organic matter turnover, soil erosion, or crop yields are not consistent because of the strong influence of local conditions (climate, soil type, and crop management). Besides, other types of environmental impacts should be taken into account in order to obtain a complete picture of the advantages and drawbacks of using straw for energy purposes. These include the leaching of nitrate, and the emissions of N trace gases such as ammonia (NH_3), nitrogen oxides (NO_x), and nitrous oxide (N_2O). The latter is particularly critical since it is major contributor to the global warming impact of agricultural systems, compared to soil C sequestration (Robertson et al., 2000). Except for nitrate leaching, there are few references on these effects in the literature, and the patterns are again not consistent across references, for the same reasons as mentioned above. The time-frame over which the effects of straw removal are investigated are also an issue. For instance, nitrate leaching was shown to decrease in the winter following the first incorporation of wheat straw in a cropping system, compared to a control with no added straw (Garnier et al., 2003). However, in another field site, this tendency was observed to reverse after a few years of continued straw incorporation (Catt et al., 1998).

In the framework of the above-mentioned research program, I used the deterministic model CERES to simulate the effect of straw removal under various sets of soil, climate and crop management conditions in northeastern France. Model results in terms of nitrate leaching, soil C variations, nitrous oxide and ammonia emissions were subsequently inputted into the life cycle assessment (LCA) of a particular bio-energy chain in which straw was used to generate heat and power in a plant producing bio-ethanol from wheat grains. Straw removal had little influence on simulated environmental emissions in the field (Table 2.3), and straw incorporation in soil resulted in a sequestration of only 5 to 10% of its C in the long-term (30 years).

The LCA concluded to significant benefits of straw use for energy in terms of global warming and use of non-renewable energy. Only the eutrophication and atmospheric acidification impact categories were slightly unfavourable to straw use in some cases, with a difference of 3% at most relative to straw incorporation (20). These results confirm the environmental benefits of substituting fossil energy with straw, while proposing a novel methodology involving process-based modelling, and evidencing its potential to take local conditions and crop management effects into account. In addition, Figure 2.16 shows how the model makes it possible to include the uncertainty due to climate variability in the analysis. Figure 2.16 reveals a strong influence of climate, while other sources of uncertainty such as soil variability and management scenarios proved less influential.

TAB. 2.3 – Average annual field emissions simulated with CERES, for use in the LCA. The selected scenarios include a winter wheat-oilseed rape-winter barley rotation, in two sites : a deep loam at Abbeville (on the North sea shore) and a rendzina soil at Fagnières (250 kms inland from Abbeville). Wheat straw is either returned to soil, which corresponds to the reference system (S1), or removed once per rotation, which corresponds the straw-based system S2. The global warming impact is calculated as the sum of C sequestration in soil organic matter (negative) and the emissions of N_2O (positive) after conversion to CO_2 based on a global warming power of 270. The contribution of N_2O is singled out.

Location	Global warming impact	N_2O part	Ammonia emission	Nitrate leaching	Crop yield Grains	Harvested straw
	kg C-CO_2 ha^{-1} yr^{-1}		kg N ha^{-1} yr^{-1}		Mg DM ha^{-1} yr^{-1}	
Reference system (S1)						
Fagnières	-800	78	16.2	5.5	7.12	0
Abbeville	-860	210	19.2	48.4	9.52	0
Straw-based system (S2)						
Fagnières	-680	78	17.0	5.0	7.14	1.05
Abbeville	-660	200	17.0	44.0	9.25	1.34

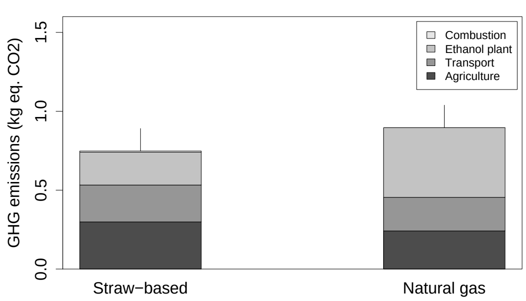


FIG. 2.16 – Effect of the inter-annual variability of CERES-simulated N_2O fluxes on the LCA results for global warming. The emissions of greenhouse gases (GHG) are aggregated over the four ethanol production stages : agricultural production, transport, conversion in ethanol plant, and straw burning. The two variant sytems are reported, involving or not the use of cereal straw in the bioethanol plant. The effect of N_2O variance on total emissions was calculated with Monte-Carlo techniques.

2.6.2 Urban waste recycling

The management of urban waste has become a major issue worldwide, with steadily growing volumes to be disposed of and increased public awareness of the resulting pressure on the environment. Amidst the range of waste treatments currently available, incineration and landfilling are the most frequent, and are commonly combined to meet the needs of local communities. However, both treatment routes raise a range of environmental problems, which have recently lead the French government to schedule a ban on most types of landfill disposal. Composting of urban waste has emerged as a valuable alternative because of the high proportion of organic matter in urban waste. The bio-degradable fraction (including food scraps, grass clippings and tree trimmings) is estimated at about 25% (fresh weight) in France, along with an additional 25% made up of paper and cardboard. Composts have long been used in agriculture, and urban waste composts (UWC) may be applied in arable fields as organic amendment to maintain soil organic matter as well as supply nutrients to crops (Stratton et al., 1995).

Similarly to bioenergy, life cycle assessment provides a relevant framework to evaluate the environmental advantages and drawbacks of waste composting, as compared to other treatment routes (Mendes et al., 2003). And likewise, the results may be expected to vary widely according to crop management, climate and soil characteristics, together with the broad range of UWC types available (Stratton et al., 1995). Process-based models may thus play a prominent role in gaining more insight into these interactions and to single out soil, climate, and management factors through scenario analysis. They may therefore help in issuing recommendation for UWC management in agriculture, regarding for instance the timing of UWC application in relation to the quality of their organic matter. Models can also approach long-term effects, which are particularly relevant to evaluate the effect of repeated applications of UWC on soil organic matter dynamics.

In the framework of a long-term field experiment set up near Grignon to evaluate the agronomic value and the environmental impacts of various types of UWC (Houot et al., 2002), I used CERES to to predict the C and N balances of the plots amended with various types of UWC. The trial is managed as a maize (Zea mays L.) - wheat (Triticum aestivum L.) rotation, and started in 1998. Comparison of observed and simulated data over the first 4 years of the field trial showed that the model predicted the soil moisture and inorganic N dynamics reasonably well, as well as the variations in soil organic C (Figure 2.17). In particular, the parameterization of UWC organic matter from biochemical fractions (as explained in section 2.14) achieved a similar fit as the parameterization based on laboratory incubation data.

Simulated N fluxes (Table 2.4) showed that the organic amendments induced an additional leaching ranging from 1 to 8 kg N ha^{-1} yr^{-1}, which can be related to the initial mineral N content of the amendments. After 4 years, the composts had mineralized 3% to 8% of their initial organic N content, depending on their stability. Composts with slower N release had higher N availability for the crops. CERES could thus be used to aid in selecting the timing of compost application, in relation to its stability, based on both environmental and agronomical criteria.

The results given in Table 2.4 were also be input into a LCA framework comparing waste composting with landfilling and incineration (86), based on available literature on this type of LCA. As underlined by a recent review (Hellebraut and Decaevel, 2004), the impacts (whether positive or negative) of field application of urban waste are a weak part of currently available LCAs. These impacts are either ignored, or approached in a very simplistic and partial manner. Compared with previous studies (Ecobilan, 1997), our estimates were significantly lower for nitrate leaching. Conversely, these studies ignored ammonia volatilization, and the introduction of our figures showed it accounted for

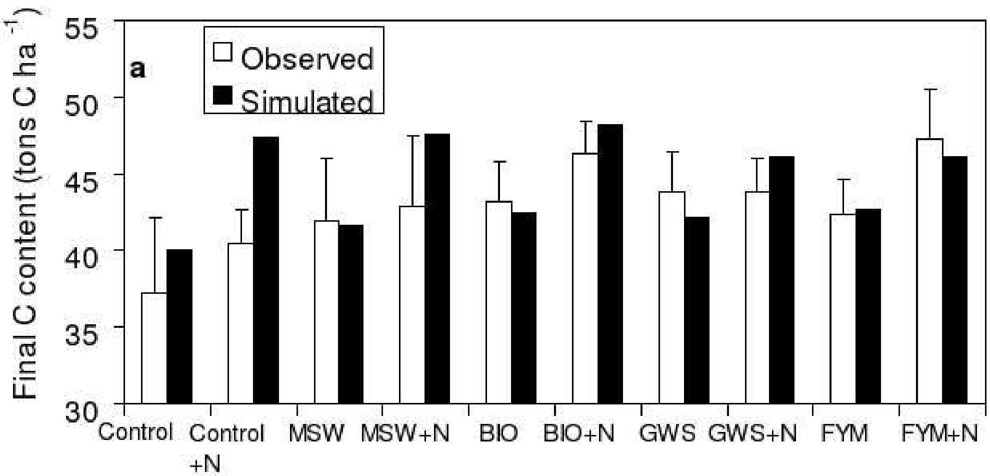


FIG. 2.17 – Bar plot of CERES-simulated versus observed variations in C stocks in the top 30 cm of soil, from Sept. 1998 to Sept. 2002 in the Feucherolles trial. Legend : MSW : municipal solid waste compost ; BIO : bio-waste compost ; GWS : green waste and sludge compost ; FYM : farmyard manure : +N : with additional application of mineral fertilizer N.

TAB. 2.4 – CERES-simulated N fluxes in the compost field trial. Fluxes are annual averages over the period running from October, 1998, to June, 2002. The fluxes for the organic treatments (MSW, BIO, GWS and FYM) are expressed as a difference relative to the corresponding controls receiving no organic amendments. Crop apparent recovery of applied N is calculated as (Treatment N uptake - Control N uptake)/(Applied N).

Flux type	Treatments				
	Control	MSW	BIO	GWS	FYM
		kg N ha^{-1} yr^{-1}			
Nitrate leaching	17.0	6.0	5.1	10.2	11.4
Denitrification	0.63	0.21	0.18	0.32	0.34
Net mineralization	82.1	17.9	15.2	24.3	27.6
Crop N uptake	86.4	20.3	16.5	27.2	34.5
Applied N[a]	8.5	137.7	140.5	162.7	124.7
		% of applied N			
Apparent crop N recovery	0	14.7	11.7	16.7	27.7

[a] : in organic and inorganic form.

Legend : MSW : municipal solid waste compost ; BIO : bio-waste compost ; GWS : green waste and sludge compost ; FYM : farmyard manure.

50% of the acidification impact of the whole chain, thereby proving a critical item in the assessment. Lastly, the impacts on soil organic matter build-up was also introduced but had very little influence on the overall results (86). Our model-based references later served in building a data base of emissions related to UWC application on arable land (77), to which I had an active contribution. The data are being taken up by reference LCA data bases such as EcoInvent (*www.ecoinvent.ch*).

The appraisal of UWC recycling also highlights potential limits of the LCA framework. A broad range of positive effects on "soil quality" may be expected, due to organic waste stimulating soil biological activity and increasing soil organic matter. These effects encompass physical, chemical and biological properties such as better resistance to compaction, increased structural stability, higher water retention capacity and cation exchange capacity, stimulation of microbial activity and degradation of soil contaminants, protection of crops against soilborne pathogens, etc... (Muller et al., 2005). However these effects are essentially qualitative, and may not be directly expressed in a format compatible with LCA, which relies exclusively on fluxes of matter and energy. It thus appears necessary to either adapt LCA in order for it to accommodate such information, or to supplement it with methods that are specifically designed for such qualitative impacts. For instance, there are currently major efforts in the field of soil microbial ecology to identify indicators of 'micro-biological quality' (76).

2.6.3 Benefits of using genetically-modified, herbicide-tolerant crops

Along with synthetic fertilizer N, pesticides are the category of inputs that epitomize the fears associated with modern agriculture worldwide (Tilman et al., 2002). Pesticides are increasingly detected in ground and surface waters in Western countries (IFEN, 2003), and also in ambient air (Bedos et al., 2002). There is thus a growing concern that the use of pesticides at current levels is not sustainable in the long run, and may lead to irreversible degradation of ecosystems and natural resources. However, reducing the doses of pesticides per hectare as is currently put forward by the EU may have drastic consequences on crop yields. Also, the environmental risks posed by pesticides is not proportional to the doses applied, but the result of its intrinsic physico-chemical and toxicological characteristics combined with the environmental conditions that determine its fate from the arable field to its final target.

Optimizing the use of pesticides thus calls for a method that would account for the effect of pesticide application on both crop productivity and environmental impacts. This is again typically the realm of life cycle assessment, which in that case would seek to minimize the marginal impacts of pesticide use per unit of final crop yield. Application of LCA would require models simulating crop response to pesticide application (ie incorporating the effect biotic stress from pests and weeds along with their response to chemicals) and models simulating the fate of pesticides in the soil-crop systems and their impacts on local or remote target ecosystems or populations. There are currently many basic components missing in that general construction. However, together with Enrique Barriuso (INRA Grignon) and a graduate student we supervised (Laure Mamy), we started working on the second part of it, in the context of genetically-modified, herbicide-tolerant (GMHT) crops. The following summarizes this work and emphasizes its most original traits.

The introduction of GMHT crops is often presented as a potential solution to reduce the environmental load of herbicides, because it leads to reduced doses of compounds that are less persistent and toxic than those used with non-GMHT crops (Wolfenbarger and Phifer, 2000; Dale et al., 2002). However, to date there are no detailed comparisons available to substantiate that claim. The objective of L. Mamy's work was thus to compare the environmental behaviour of glyphosate, as used on GMHT crops, with that of other herbicides frequently used for weed control on the same crops, albeit non-GMHT. The herbicides include trifluralin and metazachlor for oilseed rape, metamitron for sugarbeet, and sulcotrione for maize. Three experimental sites representative of the main production regions for those crops were selected, in the vicinity of three French cities : Châlons-en-Champagne, Dijon and Toulouse. These sites had hosted field trials on the introduction of GMHT crops since 1994, and the records of crop management made it possible to devise cropping systems with various degrees of GMHT crops a posteriori, along with the chemical weeding programmes. The cropping systems comprised rotations with oilseed rape and sugarbeet (GMHT or non-GMHT), and maize monoculture (GMHT or non-GMHT)

Life cycle assessment was implemented for these systems by first running a process-based model

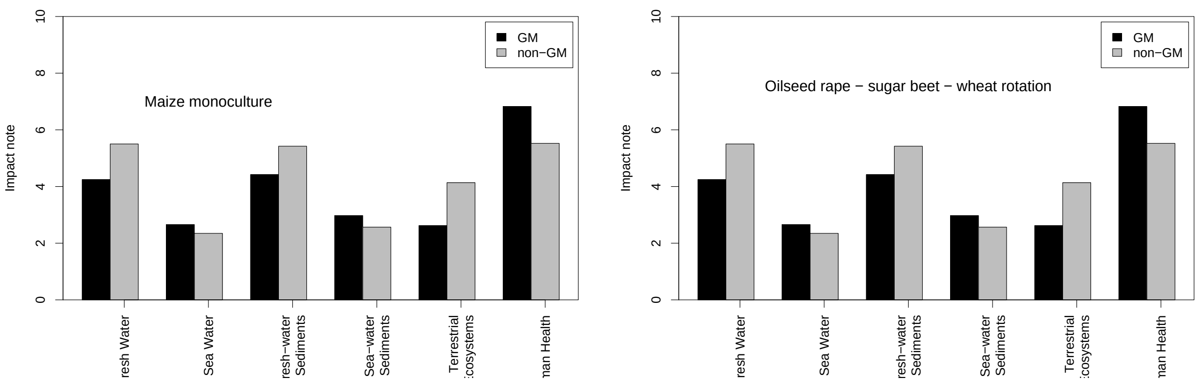


FIG. 2.18 – Calculated impacts for various cropping systems with (shallow grey) or without (dark grey) GMHT crops in Dijon. The impacts are expressed as equivalent 1,4 DCB (a reference substance for toxicological impacts), in log scale, and for 5 ecosystem or population targets : fresh and sea water, fresh- and sea-water sediments, terrestrial ecosystems, and human beings.

of pesticide fate, PRZM (Carsel et al., 1985), to estimate the fluxes and soil stocks of herbicides and their metabolites over a time period of 12 years. These variables were subsequently aggregated with the USES fate model (Huijbregts et al., 2001) to estimate the final impacts of the various cropping systems on several environmental targets (water, sediments, ecosystems, and human health). The pesticide model was parameterized from detailed laboratory studies on the sorption and degradation properties of the various molecules involved (18), and tested against field data collected in one of the sites. Some calibration was required to reach an acceptable simulation for glyphosate and trifluralin.

In most cases, glyphosate was the herbicide for which dispersal risks in the environment were lowest, because of its high sorption and quick degradation in soils. The formation of more persistent, major metabolites was observed for glyphosate (AMPA), metazachlor (unidentified) and sulcotrione (CMBA). Consequently, these metabolites present higher risks for the environment than their parent molecules and should definitely be included in the environmental assessment. The simulation of the various cropping systems and associated weed control practices showed that as the occurrence of GMHT crops increased in the rotations, the environmental impacts of glyphosate became higher compared to selective herbicides (Figure 2.18). In particular, there was a significant build-up of AMPA in soil after twelve years of annual glyphosate applications in a maize monoculture. The persistence of AMPA in soils nevertheless questions the sustainability of this innovation, and emphasizes the need for more detailed studies on the behaviour of this molecule, particularly in the long term.

Lastly, according to our LCA-based methodology, the benefits of GMHT crops varied significantly according to soil type and crop type. As exemplified on Figure 2.19, this response was not captured by the indicator I-Phy, a more simple method giving a qualitative risk of air, groundwater and surface water contamination (Girardin et al., 1999). This comparison justifies a posteriori the selection of a more complex method based on fluxes and impacts, which proved sufficiently detailed and sensitive to judge the benefits and drawbacks of introducing GMHT crops from the point of view of chemical weeding.

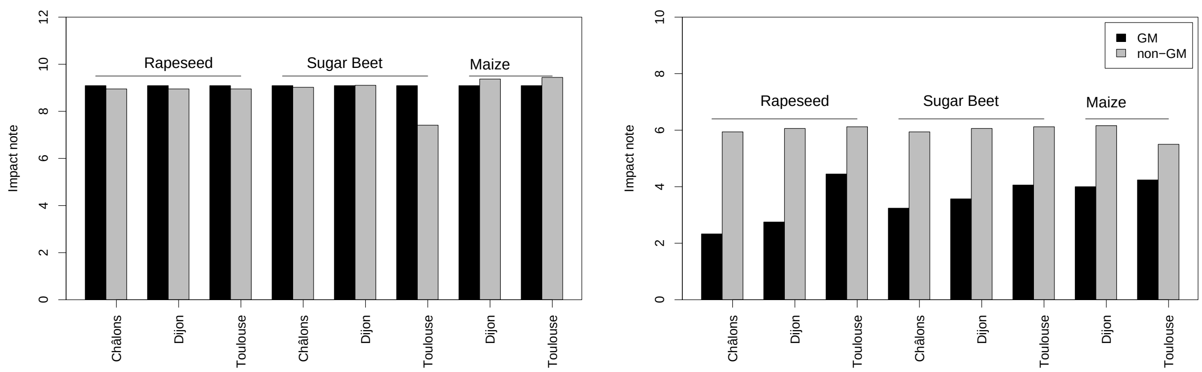


FIG. 2.19 – Effect of geographical location and crop type on the environmental impacts of GMHT (grey bars) and non-GMHT (white bars) cropping systems, assessed with two methods : the agri-environmental indicator I-Phy (right), and life-cycle assessment based on the PRZM and USES models (left). Note that the notes given by the two methods are not equivalent : I-Phy outputs a normalized score ranging from 0 (maximum impacts) to 10 (no impacts), while the USES-derived note is a flux of equivalent substance (1,4 DCB), log-transformed for graphical purposes.

2.7 Conclusion

Looking back on the past 12 years since I started working with INRA, I find myself quite lucky to have had the opportunity to develop a research programme focused on clear final objectives (implementation of an environmental assessment methodology and application to various agricultural issues), and with a precise tack (using process-based models to fill in the agricultural phases). I now realize there was a long way from plot-scale modelling to life cycle assessment since it is only now that the two are being bridged, as shown in the previous section. However, there are still many challenges ahead, as I will elaborate on in the following chapter on future research. I am also most grateful to my Ph. D. supervisor, Ghislain Gosse, for setting the course so astutely and supporting me all the way through.

The main end result of my past work is thus this evaluation scheme associating models to simulate fluxes at the arable field level, and a more comprehensive framework encapsulating the fluxes, making it possible to analyse the environmental impacts and possible improvements of the agricultural system at hand. In this process I came across many limitations and research issues, which I already highlighted in the various sections of this chapter. This short conclusion summarizes them and proposes some possible ways of addressing them.

The first series of questions deals with the ability of soil-crop models to tackle particular processes, such as gaseous emissions, which seem to require finer temporal and spatial resolutions. For instance, ammonia volatilization would be better described using hourly meteorological data and thinner layers in the topsoil (Riedo et al., 1998). This warrants further model development, along the same line as described in the above sections.

Regarding pesticide modelling, degradation and retention functions should definitely be improved. In particular, the formation of non-extractable residues is crucial in the long-term. Also, foliar application raise a host of specific issues dealing with the influence of plants on volatilization (from leaves), absorption by leaves, wash-off, and degradation once the leaves have fallen to the ground. This is especially important for post-emergence herbicides and fungicides.

Secondly, model extrapolation over larger areas requires a methodology to generate spatially-distributed estimates of model parameters, and to test the simulations over the area considered. Regarding the first point, it seems that the most critical point involves the micro-biological parameters, and most importantly those pertaining to the production of trace-gases. Discussing this issue with microbiologists has mostly convinced me that it was not to be overlooked - but most likely not resolved before a long time. The second point is part of the classical upscaling problem (Leuning et al., 2004), with several options for atmospheric emissions : using airborne techniques to measure spatially-integrated fluxes at different points in time, combining measuring towers and inverse atmospheric modelling, or ground-based measurements at random locations.
Extrapolating over long periods of time evidenced problems with the simulation of inputs from the rhizosphere, with N models like CERES giving estimates that were much lower than those given by dedicated C models like RothC. Some calibration should thus be sought, via a more realistic partitioning of photosynthates to the roots.

The application of the environmental assessment methodology proposed here does not raise research issues *per se*. It is mostly a matter of defining a strategy to respond to a demand that is on the increase, whether from the government agencies (ADEME), private companies, or other research bodies (ENSIACET, CEMAGREF, EPFL). Part of the queries originating from these partners could be answered by making our methodology available to them (*e.g.* LCA Excel sheets or simulation models), but most of the time these tools had to be tailored to the questions at hand. This has often spawned novel and most relevant, illustrating the saying that models make progress as they are being utilized. Applying the models to a variety of purposes is thus a source of enlightenment as well as a good way to anchor them into concrete ground.

However, adaptation is sometimes not enough to overcome some limits inherent to the framework chosen. This is especially true of concepts like ’soil quality’ or ’biodiversity’, which cannot be translated in terms of exchanges of matter and energy. Ecology may be expected to play a lead role in defining indicators to judge the state of these resources and the impacts of agricultural activities. It might also be necessary to look at the arable field from a broader perspective, to take into account spatial interactions between that particular field and the surrounding agro-ecosystems, or other types of ecosystems, in order to internalize some rules inherent to a higher level of organization and production (eg, forage grass). Such is the purpose of ’industrial ecology’, a relatively recent field pointing a the need for "an industrial ecosystem" in which "the use of energies and materials is optimized, wastes and pollution are minimized, and there is an economically viable role for every product of a manufacturing process" (Frosch and Gallopoulos, 1989). This analogy between a production system and a natural ecosystem, which may also be true of highly human-altered agro-ecosystems, opens new grounds for environmental optimization, partly building on more familiar tools like life-cycle-assessment.

Chapitre 3

Projet / Future research

3.1 General background

3.1.1 Emerging issues in environmental assessment

In 2004, I participated in a working group commissioned by our scientific Department to produce a report on the methodology for the environmental assessment of agricultural systems. The idea was to conduct a literary survey of current work on this topic, and to elaborate on new frontiers for research based on trends observed in the literature and on our own visions for future developments. In its conclusions, the report (76) suggested to investigate new research areas and issues, and to set up various networks to share and improve assessment methods (including models), to inventory information on current and future agricultural production systems, and to collect data on these systems at various spatial scales to implement and test the assessment methods. The research directions highlighted by the report involved :

1 a better description of the atmospheric compartment, whether as a recipient or a carrier of pollutants emitted by or deposited on agroecosystems,
2 the use of spatially-explicit methods that would take into account the interactions between cultivated fields and the fluxes of pollutants ,
3 the investigation of long-term effects of some management practices on variables like soil organic matter or biodiversity,
4 the linkage of physical and physico-chemical approaches with the ecology of the various living organisms impacted by agricultural practices,
5 quantification of the uncertainty associated with the estimated impacts,
6 taking into account the sensitivity and transport characteristics of the target environmental media (soil, water, air),
7 coupling of environmental assessment with social and economical approaches to identify better management options,
8 the co-construction of evaluation methods (models) between environmentalists and managers.

I also had the opportunity to present the early conclusions of that working group at a conference organized by the PEER (Partnership for European Environmental Research) initiative on the use of environmental indicators for sustainable development (55). The lectures and working sessions confirmed most of the above issues as particularly relevant, while emphasizing the need to better communicate about environmental indicators.

3.1.2 Short- and long-term prospects

In my past work I have already addressed some point of the above list, or at least considered them for future work. From the beginning, my focus has been on atmospheric emissions (point #1), and we are currently considering including the deposition of ammonia or ozone in the CERES model together with colleagues from my research group. As part of the same project, a graduate student I am currently supervising is linking CERES with a meso-scale model of atmospheric chemistry and transport, which will make it possible to characterize the impact of NO emissions from arable fields on the formation of tropospheric ozone - the latter being relevant to point #6. I addressed long-term dynamics regarding C and N turnover in soils (section 2.3.2), and the question of uncertainty due to inter-annual climate variability in field emissions in the LCA of straw to energy (section 2.6.1).

Most of these particular points actually involve the refinement of existing, or the development of new methodology. They open routes for future research as a direct extension of my past work, along a line consisting in improving the accuracy and scope of biophysical models for use in LCA. In the short-term, for instance, I plan on improving the ammonia volatilization and NO emission routines of CERES, for which finer temporal and spatial resolutions appear necessary. This is currently the subject of a graduate student working with me. I would also like to make some progress on the estimation of parameters for trace-gas emissions on broad spatial scales - which has proved a definite limitation in the simulation of N_2O emissions at the regional level (Figure 2.13).

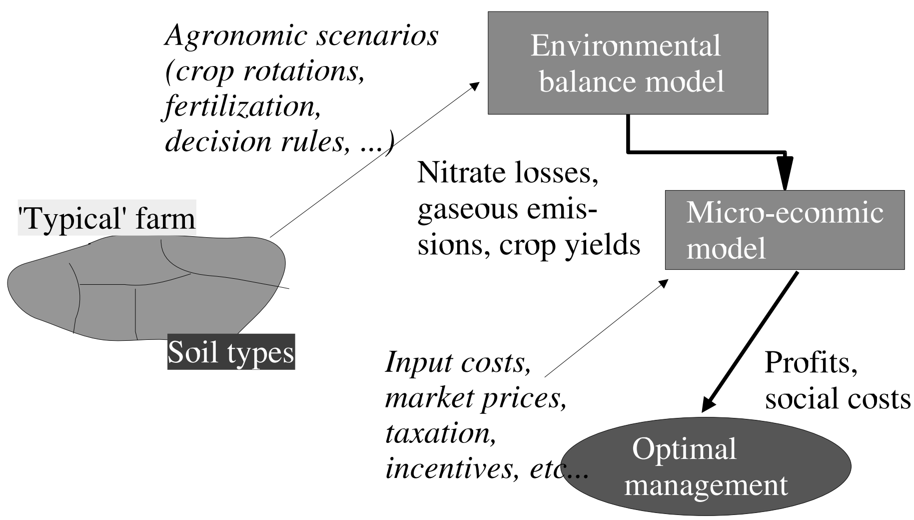


FIG. 3.1 – Schematic of an integrated approach coupling biophysical models with economic models at the farm scale. Agronomic scenarios are first selected using a random cropping systems generator and simple models to evaluate their productivity and environmental performances. The resulting scenarios are simulated with a biophysical model, which outputs yield and environmental impacts data to the LP micro-economic farm model. The latter optimizes farm management, and outputs the profits and social costs associated with pollution abatement.

In the long run, however, simply refining the LCA methodology will not be sufficient to answer some of the questions raised in the list of section 3.1.1. In particular, for LCA to be of practical use for a variety of end-users or managers, it should integrate agronomical and economical criteria. This is the purpose of last two items in the list, calling for a linkage of indicators of environmental performance at the production system level with agronomical and economical approaches. A schematic of how this joint approach might be set up is given in Figure (3.1). It shows how the production system could be optimized at the farm level, taking into account technical constraints arising from farm management and cropping systems analysis. In particular, it makes it possible to examine how economic or regulatory incentives may be used to reduce environmental pollutions form production systems. Such linkage has already been implemented for dairy cattle farms in Denmark (Vatn et al., 1999), showing abatement costs for reducing nitrate leaching to be quite high, whether for the farmer or for the government. In collaboration with colleagues from the Department of Economics, we also set up such a coupled system, with the objective of evaluating the benefits of variable-rate fertilizer application techniques (Table 3.1).

TAB. 3.1 – Effect of NPK fertilizers and wheat grain prices on the fertilizer and money savings (or losses) incurred by the use of variable-rate application techniques. The system simulated is a virtual farm of 200 ha with 100 ha of high- and low-fertility soils, respectively. The numbers in the Table correspond to the difference between the variable-rate scenario and the reference scenario with uniform application of fertilizers, obtained by combining a crop model with a micro-economic, LP^2-based model (J.-C. Hautcolas, INRA Grignon, unpublished).

Fertilizer price	Grain price	Baseline	+35%
Baseline	Money savings	479 €	851 €
Baseline	Fertilizer N savings	67 kg N	-33 kg N
+50%	Money savings	569 €	648 €
+50%	Fertilizer N savings	1033 kg N	400 kg N

3.1.3 Towards a system-based approach

Linking up with agronomic and economic models appears as an indispensable step to gain further insight into the workings and drivers of the systems at hand. It also implies working at a higher organization level - the farming system, the level at which decisions are made on the management of individual fields within the farm. Thus, the management variables that I used to consider as external drivers to the cultivated field may become endogenous to the system. This higher-level system would rather be driven by the costs of agricultural inputs, the market price of farm outputs, and a set of regulatory measures and incentives. This is particularly relevant for livestock farming, in which arable crops are only part of a picture aiming at supplying cattle with sufficient feed, and recycling animal manure. In that kind of farming systems, the management of arable crops is thus tightly connected with livestock management. Another reason for wanting to work at the farm level is that for some agricultural pollutants with relatively short residence time in the environment, the final impacts will be strongly dependent of the biophysical environment surrounding the source field. In particular, the management of the arable land in the vicinity of this source will play a major role in recapturing the compounds that have been released. This is especially true for ammonia and gaseous transport (Loubet et al., 2001), or pesticides transported via surface runoff or erosion.

Moving towards this more integrated approach leads to multi-disciplinary work with economists and agronomists, with several challenges - most notably the ability to model some practices which are currently not handled too well by models (tillage, P and K fertilization, and the effect of pesticide treatments on crop growth and yields). Also, it implies to extend the boundaries of the simulated system, to include the hydrological and atmospheric compartments in the vicinity of the fields, the objective being to simulate the fluxes of pollutants in a ’landscape’ comprising various sources and sinks. This is actually the research project of a colleague in my group, with a particular focus on N. The development of such models will be very valuable in assessing the actual impacts of reactive pollutants, and I expect fruitful interactions with this new research area.

3.1.4 Generic push and chain-specific pull

The above sections are quite general and open many perspectives, whether from the point of view of biophysical modelling, interdisciplinary work, or environmental assessment methodology. Looking at more concrete ways of researching these possibilities, there seems to be a ’generic’ push and a ’chain-specific’ pull. Until now, as I showed in this dissertation, I have always taken the particular production chains I was involved in as as many contexts in which to apply the generic methodology I was developing. Thus bio-energy, urban waste recycling or chemical weeding were only applications of this methodology. However, this approach suffers limitations in that some of the aspects considered by various stakeholders as most critical to the chain were beyond the scope of my methodology. For example, heavy metals and persistent organic pollutants are the prime concern for urban waste recycling in agriculture (Hellebraut and Decaevel, 2004). The associated categories of impacts (ecotoxicity and human toxicity) are also those for which the LCA methodology is the weakest, to date, compared to the impacts resulting from the dynamics of C and N. Also, as I underlined earlier, there are positive effects associated with repeated waste application that can not be readily translated as fluxes of matter and energy, and are therefore not yet included in LCAs. This does not mean that my work on C-N modelling and its contribution to current LCAs is irrelevant - there is also progress to be made on global warming potentials and other impacts more classical to LCA (Hellebraut and Decaevel, 2004). However, it would be more satisfactory if all these impacts could be addressed and somehow balanced to provide a complete environmental picture of urban waste recycling. The same goes to some extent for bio-energy, which may require adaptation to perennial, dedicated crops like Miscanthus, or to investigate the effect of massive cereal straw removal on soil quality (Wilhem et al., 2004).

Focusing on a particular chain would thus mean seeking to improve the environmental assessment methodology regarding the above-mentioned limitations, and potentially resorting to other assessment methods for more qualitative impacts. Although the resulting work would have some generic value, the directions taken would be essentially chain-specific. Conversely, the alternative option would consist in refining my current methodological framework, with a similar range of applications as now, and therefore focusing on the same model pollutants (N compounds and pesticides).

3.2 Future projects

Amid the range of directions proposed above for my future research, I already started working on some : the linkage with economic models, better characterization of reactive N compounds at the regional scale, improvement of emission models at the field-scale for ammonia and pesticide volatilization. They are all part of already funded research projects, which are described below. Some are yet unresolved, like the spatial estimation of microbiological parameters for trace-gas emissions from soils.
In this section, rather than giving out a detailed research plan for the 5 years to come, I will present emerging projects which are either on the generic or the chain-specific sides, and set some guidelines to ease the tension between the two sides of the question.

3.2.1 Expanding on N cycling with Nitro-Europe

NitroEurope is a recently funded EU integrated project that has been developed to “address the prime issues of European N budgets in relation to C cycling and greenhouse gas exchange, while at

the same time being aware of the interactions with other environmental issues. A key point of integration is the recognition that climate change policy requires integrated assessment of Net Greenhouse gas Exchange (NGE) rather than just CO_2. This is vital for future strategy development, since approaches that maximise CO_2 uptake may not optimize NGE. Apart from the obvious links between N and C cycles, there is a requirement to assess overall ecosystem N budgets, since other N losses, e.g. NH_3 emissions and leaching of nitrate, are considered as indirect sources of N_2O emissions under the IPCC methodology (IPCC, 1996)".
Although NEU focuses on greenhouse gases, its concept draws on the notions of life cycle and integrated impact assessment. NEU has several components involving experimental and modelling work at various scales (plot-scale, landscape, and pan-European). I will be essentially involved in plot-scale modelling of gaseous N emissions from arable fields, with various tasks : sensitivity and uncertainty analysis, model development and improvement, multi-local test on a network of monitoring sites throughout Europe, and scenario analysis. The project thus provides a strong basis to address the methodological issues involved with modelling presented in chapter 2, from the point of view of trace-gas emissions. It also gives an opportunity to link with larger spatial scales, at landscape level, and thus further the analysis of the impact of N losses from a given arable field. The project should thus result in improved generic modelling capacity in an area which is critical for the the chains I have been looking at.

3.2.2 Linking up with agronomy and economics with Praiterre

In cattle farming systems, grassland and forage crops provide key ecosystem services, whether in maintaining soil quality, regulating the N cycle and water quality, sequestering carbon in soils or safeguarding the biodiversity of soil habitats, plants, insects or other organisms. Grasslands also have indirect effects on the environment via their interactions over space and time with arable cropland. However, there is a long-standing tendency in France for grassland to be converted to arable, together with a simplification of crop rotations. The decoupling of CAP subsidies may provide an opportunity to counter this trend by striking a better balance between cereal production and cattle farming in a given territory. Such is the objective of PRAITERRE, a project coordinated by Gilles Lemaire (INRA Lusignan), and currently in the starting blocks.

The project deploys a multi-disciplinary approach combining agri-environmental engineering, socio-economic analysis of production systems, and extension activities to promote cattle farming systems relying mostly on grassland and locally-grown forage crops. (Figure 3.2). The project thus proposes to develop the systemic approach I advocated earlier on, on a range of integration scales : cropping systems, cattle production systems, and agricultural region. Each system will be investigated at its own organization level, but they will ultimately be connected through a spatially-explicit approach. That is to say, cropping systems will for instance be nested into animal production systems, whose management will determine the needs for forages and grassland on farm land. On a higher level, farms may interact within a broader geographical zone. Lastly, the organization of 'filieres' and possible niches at the regional level will determine the trajectories of individual farms or groups of farms, and ultimately the spatial patterns of land use. A pilot region was selected that includes natural ecosystems (Natura 2000 zones), to determine how agricultural land use around these zones may influence the populations of birds and other species. This regional level is indeed necessary to tackle such ecological issues.

This project combining systemic approaches at various organization levels, and disciplines such as agronomy, economics and biogeochemistry, is thus emblematic of the generic developments I envisioned in the previous section.

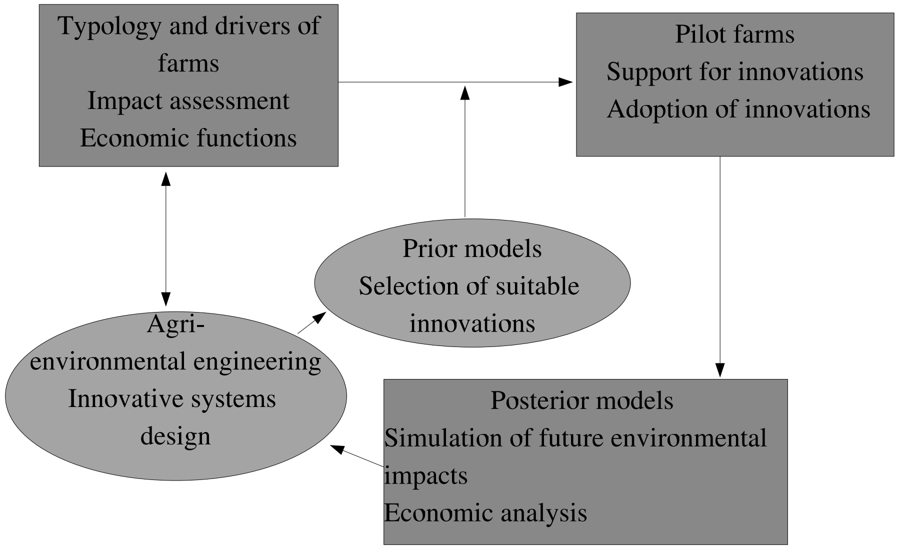


FIG. 3.2 – The research - innovation loop in the PRAITERRE project (G. Lemaire, pers. comm.)
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3.2.3 Finalizing Life Cycle Assessment with BioEnergy

BioEnergy is an EU-funded network of excellence (NoE) set up in 2003, with the purpose of supporting increased use of bioenergy through technology development and implementation, policy actions and market strategies. The RTD programme of the NoE "covers all processes, components and methods necessary for establishing successful bioenergy chains to produce heat, electricity and biofuels for the energy end use market : Planting and harvesting of biomass ; solid fuels from agricultural and forestry residues and organic waste components ; combustion, gasification and synthesis, pyrolysis, anaerobic digestion and fermentation of biomass feed stock ; production of liquid biofuels and hydrogen ; heat and power production plants ; analyses of socio-economic, policy, market and environmental issues including greenhouse gas balances."

The network has 8 core partners, and a thematic structure in work-packages (Figure 3.3). I contribute to the work-package on environmental assessment, which is mostly methodological and based on LCA, and to that on agrobiomass, coordinated by Ghislain Gosse (INRA). After a mapping of the competences and activities of the various partners, the NoE reported on the barriers to the development of bioenergy for the various chains considered. Currently, the partners are designing case-studies in which these barriers will be tackled through particular activities of research and development. The objective is to go beyond 'paper studies' until a pilot implementation showcasing a particular area of bioenergy. Economic partners are thus being involved, such as famers' cooperatives, SMEs, and local authorities. In France, the case-study considered would be in line with the cereal straw study of section 2.6.1, and supported by the French National Bioenergy Programme.
The interests of this NoE are thus twofold for me : i/ on the methodological, generic side, it provides an opportunity to collaborate with European groups on LCA in agriculture ; ii/ on the application side, it may be expected to show how this methodology may contribute to the practical development of bioenergy in a given regional context, in particular to optimize its environmental benefits.

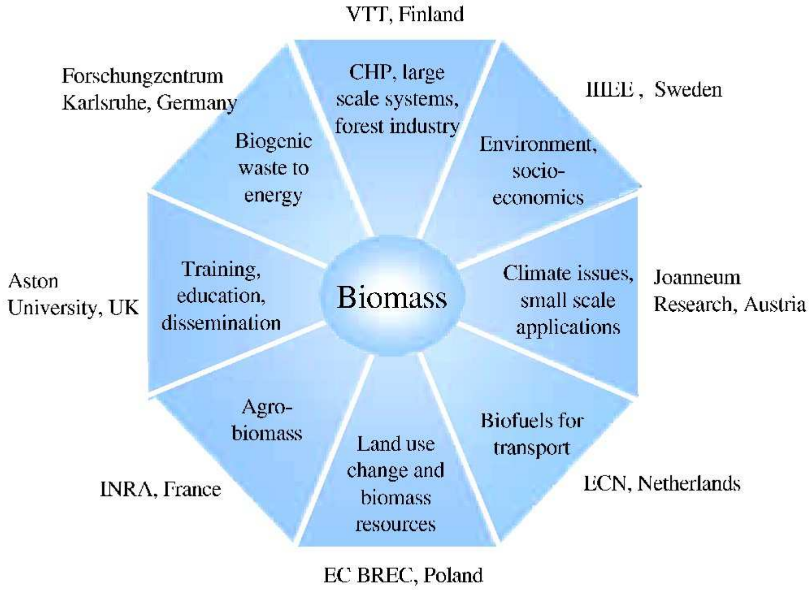

FIG. 3.3 – Structure of partnership in the BioEnergy NoE

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3.3 Epilogue - Challenges ahead

My future projects involve both some continuity and some more abrupt changes in my research, along two major lines : developing biophysically-based environmental assessment methods for agro-ecosystems, on the one hand, and fostering their application to agricultural activities in areas like bioenergy or chemical plant protection. Ultimately, the first challenge will consist of balancing the two sides of this question, so as to come up with a sound methodology associated with relevant application to meet the needs of the end-users and decision-makers. Since the second line has a potentially much broader scope than the first, the next challenge will be to team up with other research groups to tackle the environmental issues that emerge as crucial in the assessment. For instance, the recycling of urban waste raises the question of heavy metals and POPs, which have to be addressed within the evaluation. In this area I already started some cooperation with a chemistry group from the University of Toulouse. Broadening the scope of the assessment may also mean using other methods than LCA to complement its outcome with other aspects of the problem at hand.

Lastly, if the ultimate objective is to use the environmental assessment to make recommendations on a large-scale, then other aspects may come in : the overall economics of the proposed changes, social acceptability, the willingness of the various socio-economic partners involved to change their practices,... This means that my activities should be integrated within a wider, interdisciplinary research programme, while being a key driver in it. Such is actually the goal of the ’non-food use of agricultural produce’ programme that is being set up by INRA, in coordination with various R&D partners. Together with Ghislain Gosse, I intend to coordinate this programme in the near future, which is probably the most challenging task among the work ahead - albeit so fitting with an ’habilitation’ to supervise research !

Chapitre 4

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Chapitre 5

Publications choisies / Selected publications

B. Gabrielle, S. Menasseri, and S. Houot. Analysis and field-evaluation of the CERES models' water balance component. *Soil Science Society of America Journal 59 :1402-1411*, 1995.

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