Life-cycle assessment of straw use in bio-ethanol production: a case-study based on biophysical modelling

Benoit Gabrielle, Nathalie Gagnaire

Life-cycle assessment of straw use in bio-ethanol production: a case-study based on biophysical modelling.

Benoît Gabrielle* and Nathalie Gagnaire

Environment and Arable Crops Research Unit, Institut National de la Recherche Agronomique, 78850 Thiverval-Grignon, France.

*: corresponding author.

UMR INRA INA P-G Environnement et Grandes Cultures, 78850 Thiverval-Grignon, France.

Phone: (+33) 1 30 81 55 51 Fax: (+33) 1 30 81 55 63

E-mail address: Benoit.Gabrielle@grignon.inra.fr

ABSTRACT

Cereal straw, a by-product in the production of agricultural crops, is considered as a potentially large source of energy supply with an estimated value of 47×10^{18} J worldwide. However, there is some debate regarding the actual amounts of straw which could be removed from arable soils without jeopardizing their quality, as well as the potential trade-offs in the overall straw-to-energy chain compared to the use of fossil energy sources.

Here, we used a deterministic model of C and N dynamics in soil-crop systems 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, 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 8% at most relative to straw incorporation. These results based on a novel methodology thereby confirm the environmental benefits of substituting fossil energy with straw.

Key-words: C-N dynamics – cereal straw – modelling – life cycle assessment – combined heat and power generation

1 INTRODUCTION

Crop residues have recently regained attention as a potentially considerable source of renewable energy. Available residues are estimated at 10×10^9 Mg worldwide, corresponding to an energy value of 47×10^{18} J [1]. 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 from agricultural cropping systems [2]. As reviewed by the latter authors, current experimental evidences on the effects of straw removal on processes like soil organic matter (SOM) 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 being critical since it is a major contributor to the global warming impact of agricultural systems, compared to soil C sequestration [3]. Except for nitrate leaching, there are few references on these effects in the literature, and the patterns are again not consistent across references, and for the same reasons. The time-frame over which the effects of straw removal are investigated is 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 [4]. However the same tendency was reversed after a few years of continued straw incorporation in another trial [5].

Deterministic models of C-N dynamics in soil-crop systems provide a unique means of addressing the afore-mentioned issues dealing with straw removal effects. They simulate the major processes governing the impacts cited [6], and make it possible to single out soil, climate, and management factors through scenario analysis [7]. Also, they have the potential to take local context into account, which is important when assessing the environmental impacts of setting up a bio-energy chain in a particular area. Secondly, the environmental assessment should encompass the whole chain to address potential trade-offs along the chain. Life cycle assessment (LCA) provides a comprehensive, standardised framework to deal with such issues, and was already applied to straw [8, 9]. Although the results are generally favourable to cereal straw compared to various fossil feedstock (coal or natural gas), the methodology employed in these studies did not tackle the problem of ecosystem context. For instance, they all used the average emission factor of 1.25% recommended by the IPCC [10] to estimate N_2O emissions, although these are known to be highly variable in time and space [11].

In the framework of a case-study on the potential benefits of substituting natural gas with wheat straw in a bio-ethanol production plant, , we therefore set out to predict the effect of wheat straw removal on the dynamics of C and N in arable fields, including N losses (gaseous and leaching). The model is based on CERES [12], as modified to suit French conditions [13]. The second objective of this work was to use the resulting data in a LCA, and to analyze the contribution of field emissions in the overall performance of the straw-based system, compared to the reference system using solely natural gas.

2 MATERIALS AND METHODS

2.1 System definition and simulation scenarios

Our case-study involved the utilization of straw to supply heat and power to an industrial plant producing ethanol from wheat grains via biological conversion. The plant is currently in operation and located in the Picardie region, 200 kms North of Paris, France. It has a production capacity of 3 10^7 l yr^{-1}, and requires 202 10^6 MJ of primary energy per annum. In the reference system (called S1 in the following), the plant is powered only by natural gas. In the straw-to-energy system (S2), half of the energy is supplied by a straw-fueled combined heat and power (CHP) unit. The annual straw requirement thus amounts to 96 10^3 Mg (dry matter basis). Estimates of wheat straw availability around the plant resulted in a collection area of 6 000 km^2 (C. Jacquin, Arvalis, personal communication). However, the studied area was extended to a wider area of ca. 22 000 km^2, encompassing 4 administrative “departments” to investigate the impact of the plant location itself relative to the spatial availability of straw.

The study area comprises mostly cropland, of which 45% are planted with cereals. Cereals are mostly rotated with winter oilseed rape and sugar-beet, and potatoes to a little extent. The major soil types occurring in this area are luvisols, cambisols, and rendzinas (Soil Survey, INRA Orléans, France). The climate is continental, with influence from the sea in the western end of the zone. To capture the variability in environmental emissions resulting from the differences in climatic and soil conditions across the zone under study, we selected three soils representative of the major types occurring in this zone. Likewise, we selected three weather stations along a 250 km southeast-northwest transect across the study area. Table 1 gives the weather statistics for these three stations, while Table 2 lists selected characteristics of the three soils. The latter comprise an orthic luvisol, a redoxic luvisol, and a rendzina (FAO classification, [14]). In previous work, the CERES model was tested in details against experimental data for all three soils (Table 2).

CERES was run on a combination of soil types, weather stations, and crop management scenarios. Management included only two variants: the type of crop rotations in which the wheat crops were grown, and the frequency at which wheat straw was removed from the arable field. This frequency, expressed as an average of removal events per year, varied from 0% (no removal) to 100% (straw removed every year). The rotations comprised the following crops: winter wheat (WW), winter barley (WB), silage maize (SM) and grain maize (GM), sugar-beet (SB), and winter oilseed rape (WOR). The following rotations were simulated: WOR-WW-WB; WOR-WW-WW; SB-WW-WB; SB-WW-WW; SM-WW; GM-WW; WW in mono-culture. For each WW crop appearing in the rotations, two types were of straw management were simulated upon harvest: removal or soil return. Each rotation thus involved a number of variants according to the occurrence of WW in them. For instance, the WW monoculture involved four years, and thus five variants: straw removal every year; removal every two, three of four years; and no removal in any of the four years.

The rotations and their variants were run on historical series of weather data spanning the 1980-2000 time period. Crop management variables other than straw removal (fertilizer application, sowing date, etc..) were set according to current recommended practices in the area. A simple N balance was implemented in the model to calculate fertilizer N application for winter crops.

2.2 The CERES model

CERES is a mechanistic model simulating the dynamics of water, carbon and nitrogen in soil-crop systems. It runs on a daily time step and is available for a large range of arable species [12]. It runs from standard weather data incuding: solar radiation, rainfall, air temperature and potential evapo-transpiration.

CERES comprises three main sub-models. First, a physical module simulates the transfer of heat, water and nitrate down the soil profile, as well as soil evaporation, plant water uptake and transpiration in relation to climatic demand. Water infiltrates down the soil profile following a tipping-bucket approach, and may be redistributed upwards after evapo-transpiration has dried some soil layers. In both of these equations, we introduced the generalized Darcy's law in order to better simulate water dynamics in fine-textured soils [15]. Next, a micro-biological module simulates the turnover of organic matter in the plough layer, involving both mineralization and immobilisation of inorganic N. It comprises three endogenous soil OM pools: microbial biomass, active humus (‘humads’), and passive humus, which decompose according to first-order kinetics, and partly recycle into the microbial biomass. A module for predicting the emissions of N_2O via the soil nitrification and denitrification pathway was recently incorporated [16]. Also, an ammonia (NH_3) volatilization module was included in CERES [17]. Lastly, crop net photosynthesis is a linear function of intercepted radiation according to the Monteith approach, with interception depending on leaf are index based on Beer's law of diffusion in turbid media. Photosynthates are partitioned on a daily basis to currently growing organs (roots, leaves, stems, fruits) according to crop development stage. The latter is driven by the accumulation of growing degree days, as well as cold temperature and day-length for crops sensitive to vernalization and photoperiod. Crop N uptake is computed through a supply/demand scheme, with soil supply depending on soil nitrate and ammonium concentrations and root length density.

2.3 Life cycle assessment

Life cycle assessment (LCA) was conducted within the framework provided by the BioFit project [8], dedicated to the LCA of bio-fuels in european context. The analysis comprised the bio-ethanol from wheat grains chain, along with the straw for heating and triticale for CHP chains. It follows the ISO norms 14040 and 14041 regarding the various stages of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation [9]. In our case, the functional unit is one litre of ethanol, produced either using natural gas (reference system, S1) or a 50%-50% mix of gas and straw (alternative system, S2). The systems are depicted in Figure 1, which highlights the main differences between them. In the S2 system, the removal of straw results in the loss of SOM as well as nutrients, which are supplemented in mineral form. The loss of nutrients is based on the chemical composition of straw, while the SOM loss is a estimated with the CERES simulations. Since straw is considered a by-product of wheat grain production, all the emissions resulting from the cultivation of wheat are allocated to the grains [9]. The wheat straw is pressed into bales, transported by tractor to a temporary storage on the farm, prior to being collected by trucks and transported to the bio-ethanol plant. The bales are stored there for a short time and fed directly into a dedicated boiler for CHP generation. The inventory of environmental outputs was based on BioFit data, which was supplemented it with data from a more recent LCA based on the same plant under study here [18]. Following the latter study, we used a weight-based allocation ratio to partition impacts between the product of interest (ethanol) and its main by-product (wheat meal for animal feed).

The following impact categories were analysed: depletion of natural resources, global warming, atmospheric acidification, eutrophication, and potential for ozone formation. The impacts were expressed in equivalent substances: carbon dioxide (CO_2) for global warming, sulphur dioxide (SO_2) for acidification, nitrate (NO_3^-) for eutrophication, and ethene (C_2H_4) for potential ozone formation.

3 RESULTS AND DISCUSSION

3.1 Field emissions and effect of straw removal

3.1.1 Effects of soil type, geographical location, climatic year and crop rotation

Prior to analysing the effects of straw removal *per se*, it is interesting to try and rank the effects of the other factors included in the simulation scenarios, including soil type, geographical location, climatic year and crop rotation. Among them, climatic year appeared as the most sensitive factor, the other factors having a similar but smaller influence on model outputs. This is illustrated on Figure 1 in the case of wheat grain yields, which shows that inter-annual variability resulted in standard deviations up to five times higher than those resulting from the variations in crop rotation types. However, comparison with yield census data over the region shows that inter-annual variation might be over-estimated by CERES. The standard deviation calculated across the years from these data is indeed much lower than that estimated by the crop model (Figure 1), even if the census data are likely to smooth out variability because they represent regional averages as opposed to the field-scale simulations provided by CERES. The latter also over-estimated the average harvested yield by 10% to 35%, which is not surprising since the model does not include the effect of pests and diseases, as well as grain losses upon harvest.

Over the four combinations of soil type and climate tested in Figure 1, the time-averaged grain yields varied within a 2 Mg ha^{-1} range, the two extremes occurring with the rendzina in the drier climatic location (Fagnières), and the deep loam in the wetter location (Abbeville). We considered the latter two combinations as regional extremes, given that the third soil type (redoxic luvisol) represented a medium situation in terms of simulated grain yields, whatever the climatic location. This also applied to the other model outputs, with the exception of ammonia emissions, which were lower by 10 to 15 kg N ha^{-1} yr^{-1} with the redoxic luvisol than with the other two soils.

Regarding outputs other than crop yields, the effect of climatic location and soil type may be analysed by comparing the four situations resulting from the combination of the above two extreme soils (rendzina and deep loam) and climatic locations (Abbeville and Fagnières). Switching from the wetter location (Abbeville) to the drier one (Fagnières) with the deep loam resulted in a grain yield decrease of 1 Mg DM ha^{-1}, on average. Deep drainage also decreased 132 mm, which is very close to the 138 mm difference in annual rainfall across the two locations (Table 1). As a consequence, nitrate leaching decreased 14.6 kg N ha^{-1} yr^{-1} in the drier climate compared to the wetter one. Conversely, with the rendzina soil, switching to a wetter climate resulted in a slight increase in grain yields (0.3 Mg DM ha^{-1}), two-fold higher amounts of deep drainage, and an 8 kg N ha^{-1} yr^{-1} increase in nitrate leaching on average. In both soils, nitrous oxide emissions were relatively low, ranging from 0.15 to 0.60 kg N-N_2O ha^{-1} yr^{-1}. This was especially true for the rendzina soil due to its alkaline pH, which is known to reduce N_2O production from denitrification [19]. The emissions were little affected by climate, decreasing at most 0.20 kg N ha^{-1} yr^{-1} when switching to the drier climate with the deep loam. Ammonia volatilisation increased 80% in the drier climate relative to the wetter one, whether with the deep loam or the rendzina soil.

CERES predicted a net increase in soil organic matter all soils, even when straw was removed most of the years. The variations in SOM were very similar across climates, and ranged from 0.15 to 0.75 Mg C ha^{-1} yr^{-1}, with the exception of the rotation involving grain maize for which the increase was much higher, ranging from 1.0 to 1.3 Mg C ha^{-1} yr^{1}. These values fall in the higher part of the -2.0 to 2.0 Mg C ha^{-1} yr^{-1} range reported for arable soils in the area over the 1970-1998 time period [20], regardless of crop rotations and straw management.

3.1.2 Effect of straw removal frequency on model outputs

Figures 3 and 4 show the effects of crop rotation and straw removal frequency on various model outputs for the two extreme combinations of soil and climate: the rendzina at Fagnières and the deep loam at Abbeville. The differences across rotations are generally more important than those related to straw management for a given rotation. The removal of straw thus bore little effect on field emissions. The highest effects were noted on crop productivity, with grain yield being negatively affected by straw removal because of a lower net mineralisation of N in soils. The yield losses ranged between 0.05 to 0.15 tons DM ha^{-1} for each ton of straw removed, which is in line with the 0.13 Mg grain DM ha^{-1} loss reported for various crops in the US [2]. This corresponds to a straw fertiliser value ranging from 1.5 to 4.5 kg N Mg^{-1} straw, which is lower than the total N content of the straw, estimated at 6 kg N Mg^{-1} straw DM [21]. Harvested straw yields paralleled grain yields, and varied between 1.0 and 4.6 Mg straw DM ha^{-1} when averaged over the whole rotation (Figure 3, middle).

Regarding the environmental emissions, nitrate losses tended to decrease with increasing straw removal in all cases (Figure 4, middle). This represents the balance between two opposite effects: in the short-term, straw incorporation was shown to decrease nitrate leaching because of a temporary immobilisation of mineral N by soil microflora [4, 22]. This effect is not always noted [23], for instance if straw residues are relatively rich in N [24]. In the longer term on the other hand, after several years of continued incorporation, the increase in SOM may lead to higher, uncontrolled N mineralization, and to higher nitrate losses as a consequence [5]. Such was the case in the CERES simulations, which spanned 30 years.

Similarly to nitrate leaching, N_2O emissions decreased slightly with increasing straw removal, with a rate of 0.1 to 0.25 kg N Mg^{-1} straw DM (Figure 4, top). There is little information on such effect in the literature, but the available results generally emphasize the links with N fertilization: straw return to soil increases to soil's denitrification potential, and to a some extent its capacity to produce N_2O [25], but decrease it temporarily in case the incorporation of straw is followed by an application of mineral of organic fertilizers [26, 27]. This was however not the case here. Nitrous oxide emissions were converted in CO_2 equivalent using a global warming potential of 270, which corresponds to a 100-yr projection [28]. They were subsequently aggregated with the C balance of the soil to estimate the net impact of the cropping system on global warming. Straw removal contributed to increase the global warming impact in both locations (Figure 3, top), by one Mg equivalent CO_2 ha^{-1} on average, due to the contribution of incorporated straw to SOM in the long-term. Over the 30-yr simulation period, the model simulated a sequestration potential ranging from 0.05 to 0.1 Mg C Mg^{-1} of added straw DM, being lowest for the SB-WW-WW rotation in Fagnières. These figures are in the higher range of the values reported in a recent review [29], namely a range of 0.01 to 0.04 Mg C Mg^{-1} straw DM. Wilhem et al. [2] cited a much broader range (0.0 to 0.1 Mg C Mg^{-1} straw DM), but noted a major interaction with tillage. Here, the type of rotation was also decisive as regards the sequestration capacity of the cropping system, whether the wheat straw was removed or not. The rotation involving grain maize has the highest sequestration potential because of the high level of residue return from the maize crops.

Ammonia volatilisation correlated negatively with the rate of straw removal in Fagnières, and positively in Abbeville (Figure 4, bottom). These two opposite cases reflect different balances between the two factors which could explain the effect of straw management on NH_3 volatilization: on the one hand, incorporating straw in soil increases its capacity to immobilize mineral fertilizer N, and thus decreases the availability of ammonium to volatilization; on the other hand, straw incorporation increases the net mineralization of nitrogen, being produced in the ammonium form, which is likely to increase NH_3 volatilisation. However, as observed after application of urea [30], straw management had little effect on volatilization. The maximum differences between the treatments with total straw return to soil and straw removal ranged from 1 to 2 kg N-NH_3 ha^{-1} yr^{-1} in Fagnières, representing only 5 à 10% of the absolute emissions, and these deviations were similar in Abbeville except for two rotations.

Lastly, we tested the influence of the timing of straw removal within the rotations, and found it negligible. There was also very little effect of straw management on the water balance, with straw removal either slightly increasing (Fagnières) or decreasing (Abbeville) deep drainage. Straw removal also decreased annual evapo-transpiration by a few percents, because of its slightly decreasing crop yields.

3.2 Life cycle assessment

For the purposes of the LCA, we selected one crop rotation which was judged representative of the other rotations, namely the WOR-WW-WW rotation. Table 3 summarises the direct emissions data simulated by CERES for the two extreme soil and climate combinations (the rendzina soil in Fagnières and the deep loam in Abbeville), averaged over time. The main differences between the two soils may be summarised as follows: the deep loam emitted more nitrate than the rendzina by an order of magnitude, three times as much nitrous oxide, and similar levels of ammonia, while achieving 25% higher yields (Table 3). Originally, there were two variants for that rotation, since wheat straw could be removed once or twice per rotation. Since the simulated emissions differed only by a few percents between the two variants, we decided to consider only the first one (straw removed once per rotation).

These emissions were inputted to the LCA of the two systems (S1 and S2), whose results are shown in Table 4, while Figure 5 shows their breakdown among the various phases (agricultural production, transport of grains and straw to the ethanol plant, conversion to ethanol, combustion of straw and ash disposal). As could be expected [8, 9], the substitution of natural gas with straw resulted in a significant reduction of in the global warming impact, along with non-renewable energy consumption. For each litre of ethanol produced, the relative differences between the reference and straw-based systems amounted to 20% for these two impact categories. When the differences in primary energy consumption between S1 and S2 were expressed relative to the amount of straw used in S2 (Table 4), it is interesting to note that they corresponded to the lower heating value (LHV) of straw, which is of 15 MJ kg^{-1} DM. Likewise, the CO_2 savings correspond to 100% of the theoretical substitution potential for natural gas, since the latter contains 53 g CO_2 per MJ of LHV [31]. This represents 50% of the straw's total C content. The S2 system was thus very efficient at substituting fossil energy and carbon with non-renewable feedstock. This stems from the fact that, compared to natural gas, the extra energy required in the S2 system to collect the straw and manufacture and operate the straw boiler was 20 times lower than the natural gas savings incurred by the use of straw (Figure 5).

Regarding the other three categories within the scope of the present LCA, the differences were either nil (ozone creation potential), or dependent on the location considered. Compared to the reference system S1, acidification was 8% higher in the S2 system in Fagnières and 5% lower in Abbeville, whereas eutrophication was 3% lower in Fagnières and 0.2% higher in Abbeville. These variations resulted from differences in the two sites in terms of nitrate leaching and ammonia emissions response to straw removal, as discussed in the previous section. They emphasize the influence of local ecosystem context on the overall results of the LCA, which also appeared in the energy balances: the latter were less favourable in Fagnières compared to Abbeville because the yields were lower. The efficiency of the agricultural production phase was thus decreased. Lastly, it should be noted that the straw boiler emitted more compounds involved in eutrophication (in the form of NO_x and NH_3) than the natural gas boiler, due to the higher N content of straw. It may thus be argued that crop management could be adjusted to decrease the N content of straw, however it is likely to be antagonistic with grain quality targets in terms of protein content, if the wheat grain is marketed for food purposes.

3.3 Conclusions

Using the framework of life cycle assessment, we evaluated the interest of substituting cereal straw for natural gas for combined heat and power generation in a bio-ethanol plant. As already shown in previous studies, the main benefits lied in the saving of non-renewable resources and the reduction of greenhouse gas emissions, which proved very efficient. The picture was mitigated regarding other impacts such as eutrophication or acidification, whose outcome actually depended on local ecosystem context (ie, soil type and climatic zone). The use of a biophysical model made it possible to take such factors into account, substantiating the idea that impacts occurring on a local scale should be addressed based on local characteristics rather than on national or global averages. This will ultimately mean that some biomass production zones will emerge as performing better than others, from the point of view of environmental impacts, and thus induce some kind of spatial differentiation with respect to the implementation of biomass chains. Although this idea is rather intuitive, it had not been implemented yet in life cycle assessment. The use of biophysical models may therefore be expected to play a crucial role in the future development of this methodology.

The impacts related to human toxicity and eco-toxicity were disregarded in this study, although they might play a significant role, especially during the straw burning phase. We had decided such impacts lied beyond the scope of the present study, since it was focused on the agricultural production phase and the use of crop residues, which do not directly involve the use of agrochemicals. Also, the data available for toxicity assessment are limited and the methodology is still under development [32]. Future work along this line is therefore essential to provide a more complete picture of straw to energy chains.

4 ACKNOWLEDGEMENTS

The authors would like to thank J. Da Silveira for her help in the CERES simulations, and Jean-Claude Sourie for coordinating the research project within which this work was carried out. Financial support was provided by the AGRICE grant programme (ADEME, France).

5 REFERENCES

[1] Lal R. World crop residues production and implications of its use as a biofuel. Environ Internat 2005; 31:575-584.

[2] Wilhem WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR. Crop and soil productivity response to corn residue removal: a literature review. Agron J 2004; 96:1-17.

[3] Robertson GP, Paul EA, Harwood RR. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 2000; 289:1922-1925.

[4] Garnier P, Neel C, Aita C, Recous S, Lafolie F, Mary B. Modelling carbon and nitrogen dynamics in a bare soil with and without straw incorporation. Eur J Soil Sci 2003; 54:555-568.

[5] Catt JA, Howse KR, Christian DG, Lane PW, Harris GL, Goss MJ. Strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK, 1988-93: the effect of straw incorporation. J Agric Sci (Camb) 1998; 131:309-319.

[6] Diekkrüger B, Söngerath D, Kersebaum KC, McVoy CW. Validity of agroecosystem models. A comparison of results of different models applied to the same data set. Ecol Model 1995; 81:3-29.

[7] Ramanarayanan TS, Storm DE, Smolen MD. Analysis of nitrogen management strategies using EPIC. J Am Water Resour Ass 1998; 34:5.

[8] Reinhardt GA. Bio-energy for Europe. Which ones fit best? Rapport final projet Biofit. Heidelberg: IFEU; 2000.

[9] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal. Energy and emission balances from a German case study. Biomass and Bioenergy 1999; 16:397-406.

[10] IPCC. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reporting Instructions (Volume 1). wwwipccch 1997.

[11] Li C, Zhuang YH, Cao M, Crill PM, Dai ZH, Frolking SE et al. Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N2O emissions from arable lands in China. Nutr Cycling Agroecosys 2001; 60:159-175.

[12] Jones CA, Kiniry JR. Ceres-N Maize: a simulation model of maize growth and development. Temple, TX: Texas A&M University Press, College Station; 1986.

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

[14] Fao Unesco ISRIC. Carte mondiale des sols, légende révisée. Rapport sur les ressources en sols du monde, Rome: Food and Agriculture Organization; 1989.

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

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

[17] Génermont S, Cellier P. A mechanistic model for estimating ammonia volatilization from slurry applied to bare soil. Agric For Meteorol 1997; 88:145-167.

[18] ADEME. Non-technical barriers to the development of liquid bio-fuels in Europe. Final project report, EEC Altener Programme. Altener; 1995.

[19] Hénault C, Cheneby D, Heurlier K, Garrido F, Perez S, Germon JC. Laboratory kinetics of soil denitrification are useful to discriminate soils with potentially high levels of N2O emission on the field scale. Agronomie 2001; 21:713-723.

[20] Wylleman R, Mary B, Machet JM, Guérif J, Degrendel M. Evolution des stocks de matière organique dans les sols de grande culture: analyse et modélisation. Persp Agricoles 2001; 270:8-14.

[21] SOLAGRO. Faisabilité écologique de la valorisation énergétique de la paille en Ile-de-France. Toulouse: ARENE Ile de France / ADEME; 2001.

[22] Silgram M, Chambers BJ. Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. J Agric Sci (Camb) 2002; 139:115-127.

[23] Thomsen IK, Christensen BT. Cropping system and residue management effects on nitrate leaching and crop yields. Agric Ecosys Environ 1998; 68:73-84.
[24] Mitchell RDJ, Webb J, Harrison R. Crop residues can affect N leaching over at least two winters. Eur J Agron 2001; 15:17-29.
[25] Avalakki UK, Strong WM, Saffigna PG. Measurements of gaseous emissions from denitrification of applied 15-N. 2. Effects of temperature and added straw. Austr J Soil Res 1995; 33:89-99.
[26] Cai Z, Laughlin RJ, Stevens RJ. Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment. Chemosphere 2001; 42:113-121.
[27] Hao X, Chang C, Carefoot JM, Janzen HH, Ellert BH. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. Nutr Cycling Agroecosys 2001; 60:1-8.
[28] IPCC. Revised IPCC [Intergovernmental Panel on Climate Change] Guidelines for National Greenhouse Gas Inventories: Bracknell, UK; 1996.
[29] Soussana JF, Arrouays D, Balesdent J, Chenu C, Ciais P, Gabrielle B et al. Usages du sol, stockage de carbone et effets connexes: état de l'art. In:Arrouays D, Balesdent J, Germon JC, Jayet PA, Soussana JF, Stengel P, Arrouays D, Balesdent J, Germon JC, Jayet PA, Soussana JF, Stengel Ps. Stocker du carbone dans les sols agricoles de France ?, Paris: INRA Expertise collective; 2002, p. 131-133.
[30] Tian GM, Cai ZC, Cao JL, Li XP. Factors affecting ammonia volatilisation from a rice-wheat rotation system. Chemosphere 2001; 42:123-129.

[31] Riedacker A. Effet de serre et politiques de lutte contre le changement climatique. Mondes en développement 2003; 31:47-70.

[32] Pant R, Hoof Gv, Schowanek D, Feijtel TCJ, Koning Ad, Hauschild M et al. Comparison between three different LCIA methods for aquatic ecotoxicity and a product environmental risk assessment: insights from a detergent case study within OMNIITOX. Int J LCA 2004; 9:296-306.

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

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

Table 1. Weather statistics for three sites along an East-West transect across the studied area.

Site name	Cumulative rainfall	Cumulative potential evapo-transpiration	Mean air temperature	Mean global radiation
	mm yr^{-1}		°C	MJ m^{-2} d^{-1}
Abbeville	747	637	10.3	10.65
Fagnières	636	694	10.4	11.55
Mons-en-Chaussées	627	665	10.6	10.73

Table 2. Selected properties of the representative soils used in the field simulations. The references describe the test of CERES against experimental data for the various soils.

Soil classification (FAO)	Selected properties				Reference
	Topsoil texture (UDSA triangle)	pH	%C	%CaCO3	
Orthic Luvisol	loam	7.8	1.2	1	[13]
Redoxic Luvisol	silt-loam	6.9	1.1	< 1	[33]
Rendzina on chalk	silt-loam	8.7	1.9	75	[34]

Table 3. Field emissions used in the LCA for the selected agronomic scenarios: the rendzina soil at Fagnières, and the deep loam at Abbeville, for the oilseed rape-wheat-wheat rotation. 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 emissions are averaged over the various climatic years simulated. The global warming impact is calculated as the sum of C sequestration in soil organic matter (negative) and the emissions of N_2O, converted to CO_2 based on a global warming power of 270. The contribution of N_2O is singled out.

Location	**Global warming impact**		**Ammonia**	**Nitrate leaching**	**Crop yield**	
		N_2O part			Grains	Harvested straw
	kg eq. C-CO2 ha^{-1}		kg $N\text{-}NH_3$ ha^{-1}	kg N-NO3 ha^{-1}	Mg DM 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

Table 4. LCA results for the reference (S1) and straw-based (S2) systems, for the selected agronomic scenarios involving the rendzina soil at Fagnières and the deep loam at Abbeville. For system S2, fluxes are expressed as a difference relative to S1 (S2 - S1). A positive value thus indicates a reduction in environmental impact. The functional unit is one litre of bio-ethanol in the S1 and (S2 - S1) columns, whereas in the rightmost column the fluxes are expressed relative to one kg of straw dry matter used in the bio-ethanol production process.

Impact category	**Unit**	**S1**	**(S2 - S1)**	**(S2-S1)/kg of straw**
Non-renewable	**energy**	**consumption**		
Fagnières	MJ	13.0	*3.2*	15.1
Abbeville	MJ	12.3	*3.2*	14.9
Global warming	**(100 years)**			
Fagnières	g eq. CO_2	977.1	*165.1*	- 780
Abbeville	g eq. CO_2	918.4	*160.1*	- 762
Acidification				
Fagnières	g eq. SO_2	9.6	*- 0.7*	3.12
Abbeville	g eq. SO_2	7.9	*0.3*	1.21
Eutrophication				
Fagnières	g eq. NO_3	24.0	*- 0.7*	3.06
Abbeville	g eq. NO_3	40.8	*0.8*	- 4.11
Ozone creation	**potential**			
Fagnières	g eq. Ethen	0.3	*0.01*	- 0.02
Abbeville	g eq. Ethen	0.3	*0.00*	- 0.02

Figure captions

Figure 1. Schematic of the reference system (S1, solid line) and the straw-based system (S2, dashed line). In the S2 system, the CHP in the ethanol conversion plant is operated from a 50%-50% mix of straw and natural gas.

Figure 2. Effect of soil type, geographical location (Fagnieres or Abbeville – Abbe.) and climatic year on the wheat yields simulated by CERES. The bars correspond to the mean yields averaged over the various climatic years and crop rotations simulated for each combination of soil type and geographical location. Two series of error bars are shown: one corresponding to the standard deviation across the various crop rotation and straw removal scenarios (n=20), and the other to the average standard deviation across the various climatic years (n=31). The last bar shows the average yield, as estimated from the census data over the study area, and the standard deviation over the 1980-1995 period.

Figure 3. Effect of straw removal frequency on the emissions of N_2O (top), nitrate (middle), and ammonia (bottom) in the rendzina and deep loam soils, for the various rotations (WOR-WW-WW: ●; WOR-WW-WB: ○; SM-WW: ▲; GM-WW:Δ; SB-WW-WW: ■; SB-WW-WB: □; wheat mono-culture: ◊). The solid lines are linear regressions against straw removal frequency for each rotation. Note the differences in scales for the *y*-axis between the two soils.

Figure 4. Effect of straw removal frequency on cropping systems' greenhouse gas (GHG) balance (top), straw output (middle), and wheat grain yields (bottom) in the rendzina and deep loam soils, for the various rotations (WOR-WW-WW: ●; WOR-WW-WB: ○; SM-WW: ▲; GM-WW:Δ; SB-WW-WW: ■; SB-

WW-WB: □; wheat mono-culture: ◊). The solid lines are linear regressions against straw removal frequency for each rotation. The GHG balance, expressed in equivalent CO_2 net emissions, compounds two items: N_2O emissions, and soil carbon content variations.

Figure 5. Breakdown of the bio-ethanol LCA results among the various production phases: agricultural production (AGRICULT), transport of grains and straw to ethanol plant (TRANSPORT), conversion of wheat grains to ethanol (EtOH), combustion of straw and ash disposal (COMBUSTION). S1 is the reference system while S2 is the straw-based system, and the agronomic scenario corresponds to the deep loam soil.

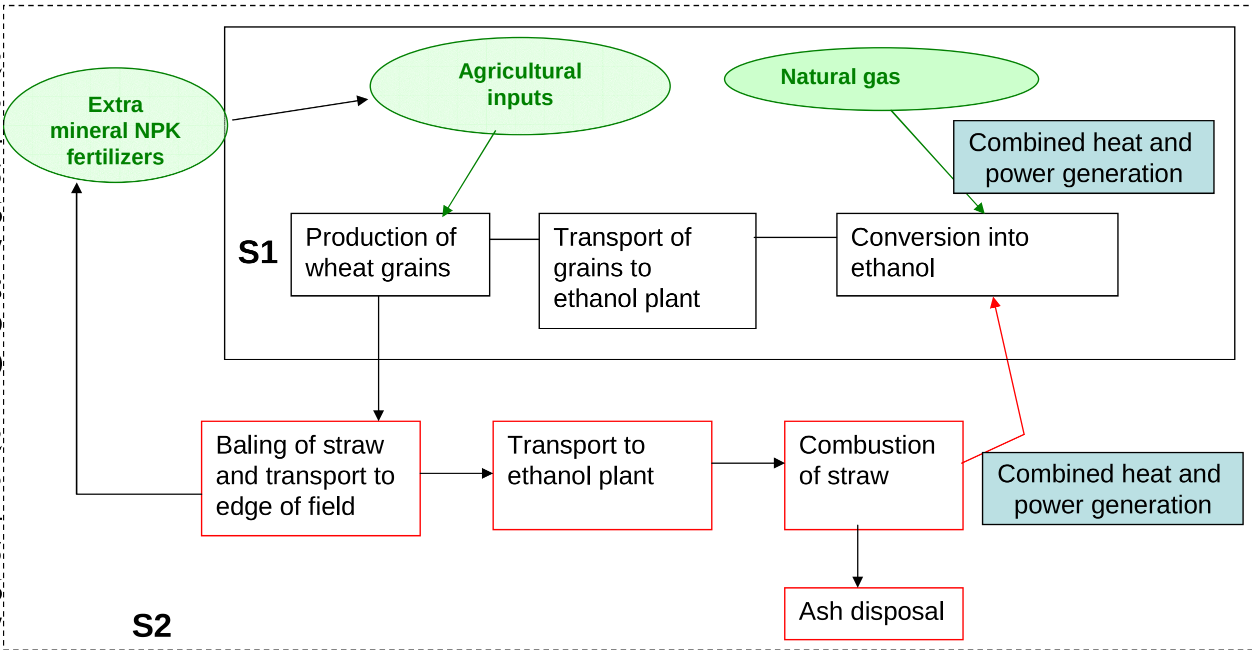

Agricultural inputs
Natural gas
Extra mineral NPK fertilizers
Combined heat and power generation
S1
Production of wheat grains
Transport of grains to ethanol plant
Conversion into ethanol
Baling of straw and transport to edge of field
Transport to ethanol plant
Combustion of straw
Combined heat and power generation
Ash disposal
S2

Figure 1

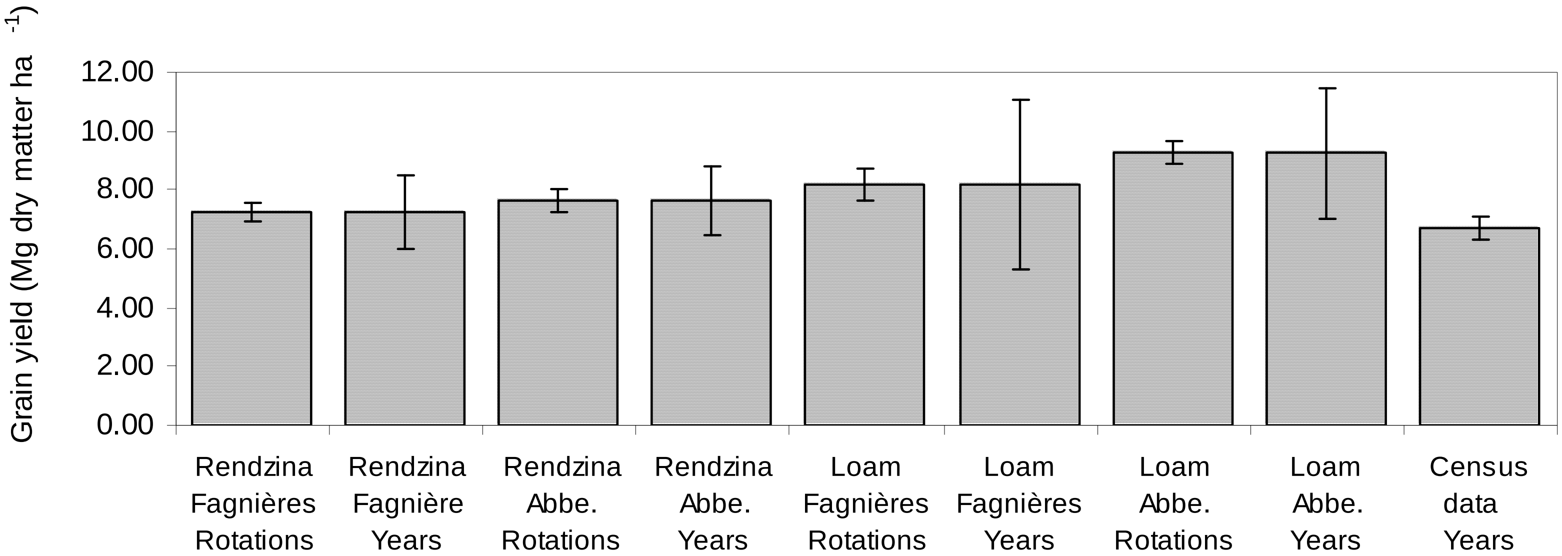
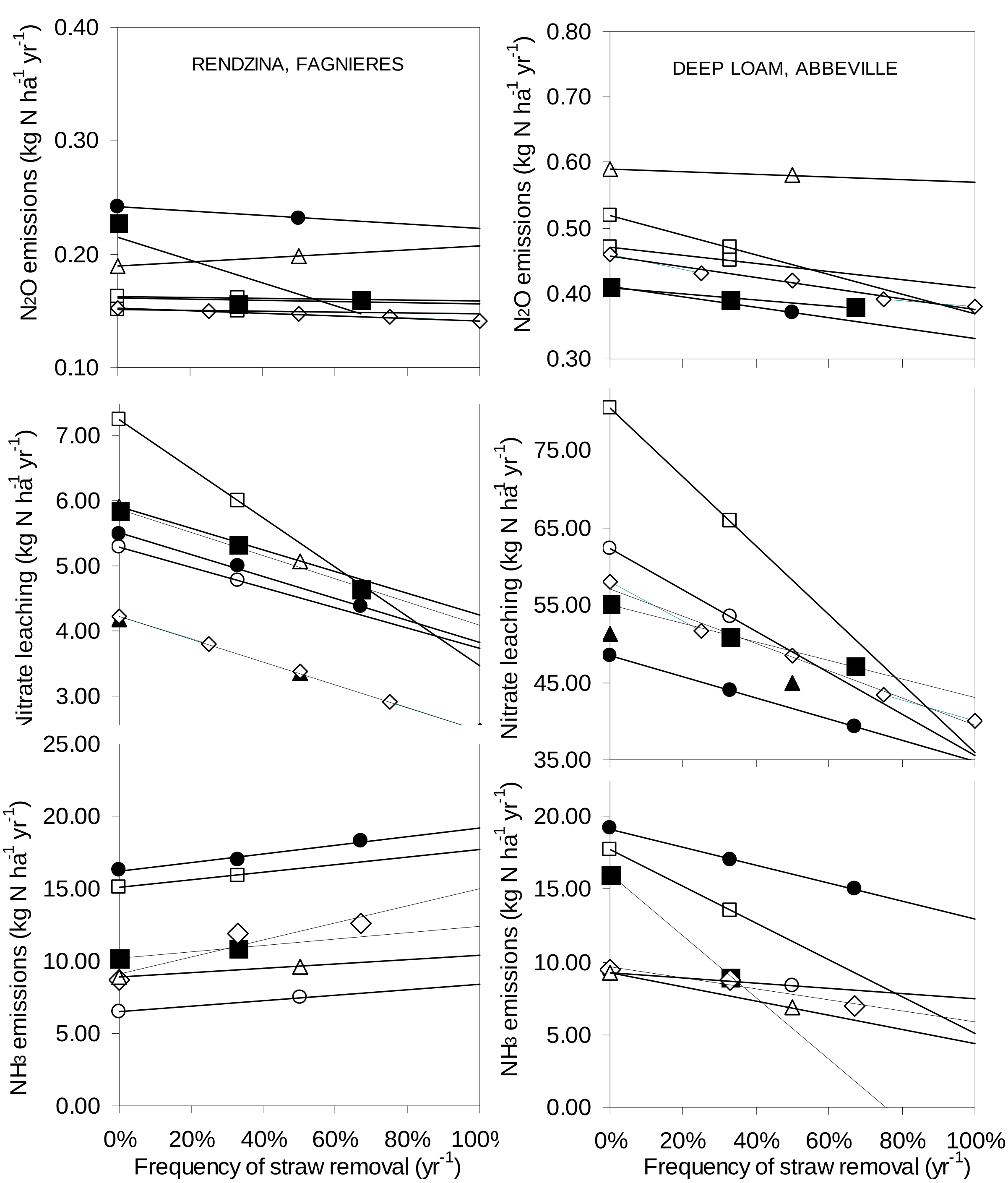

Grain yield (Mg dry matter ha -1)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Rendzina Fagnières Rotations
Rendzina Fagnière Years
Rendzina Abbe. Rotations
Rendzina Abbe. Years
Loam Fagnières Rotations
Loam Fagnières Years
Loam Abbe. Rotations
Loam Abbe. Years
Census data Years

Figure 2



RENDZINA, FAGNIERES
DEEP LOAM, ABBEVILLE
N2O emissions (kg N ha-1 yr-1)
Nitrate leaching (kg N ha-1 yr-1)
NH3 emissions (kg N ha-1 yr-1)
Frequency of straw removal (yr-1)

Figure 3

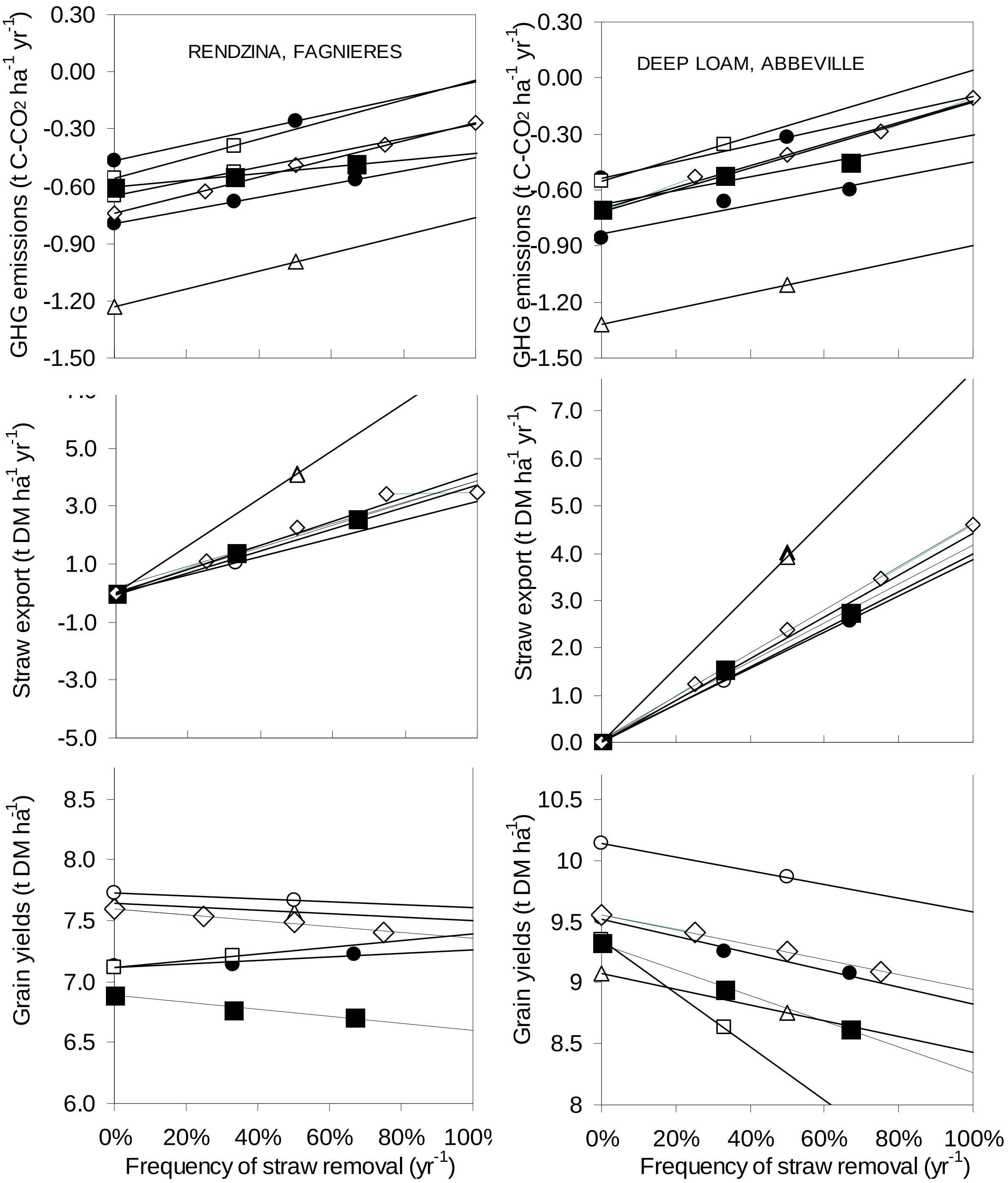

RENDZINA, FAGNIERES
DEEP LOAM, ABBEVILLE
GHG emissions (t C-CO2 ha-1 yr-1)
0.30
0.00
-0.30
-0.60
-0.90
-1.20
-1.50
Straw export (t DM ha-1 yr-1)
5.0
3.0
1.0
-1.0
-3.0
-5.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Grain yields (t DM ha-1)
8.5
8.0
7.5
7.0
6.5
6.0
10.5
10
9.5
9
8.5
8
0%
20%
40%
60%
80%
100%
Frequency of straw removal (yr-1)

Figure 4

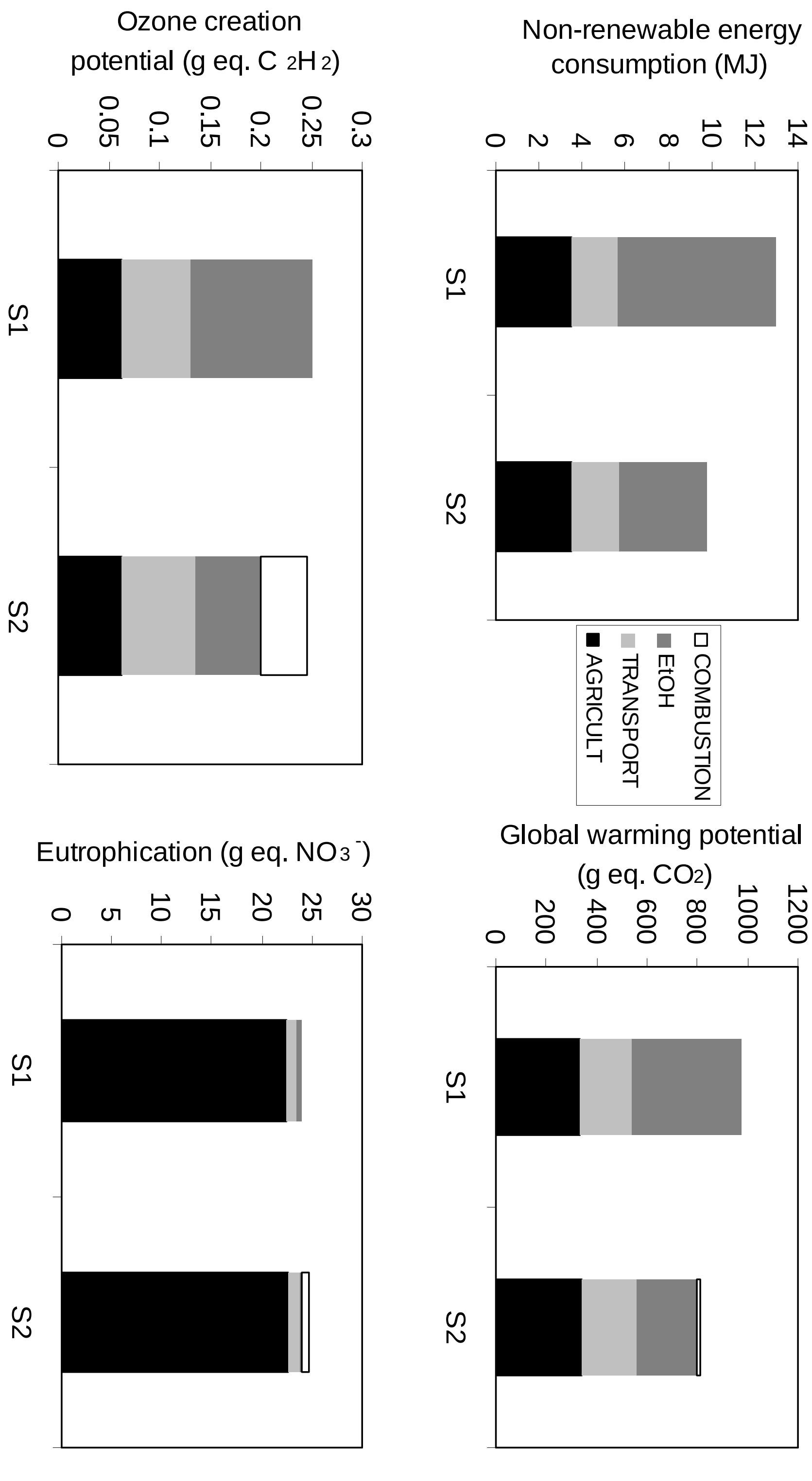

Non-renewable energy consumption (MJ)
Global warming potential (g eq. CO_2)
Ozone creation potential (g eq. C_2H_2)
Eutrophication (g eq. NO_3^-)
COMBUSTION
EtOH
TRANSPORT
AGRICULT
S1
S2

Figure 5