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

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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.

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

1 INTRODUCTION

2 Crop residues have recently regained attention as a potentially considerable
3 source of renewable energy. Available residues are estimated at 10×10^9 Mg
4 worldwide, corresponding to an energy value of 47×10^{18} J [1]. Among them, cereal
5 residues are the largest source, making up two thirds of the total available amount.
6 However, there is an on-going debate on the actual possibilities of straw removal
7 from agricultural cropping systems [2]. As reviewed by the latter authors, current
8 experimental evidences on the effects of straw removal on processes like soil
9 organic matter (SOM) turnover, soil erosion, or crop yields are not consistent
10 because of the strong influence of local conditions (climate, soil type, and crop
11 management). Besides, other types of environmental impacts should be taken into
12 account in order to obtain a complete picture of the advantages and drawbacks of
13 using straw for energy purposes. These include the leaching of nitrate, and the
14 emissions of N trace gases such as ammonia (NH_3), nitrogen oxides (NO_x), and
15 nitrous oxide (N_2O), the latter being critical since it is a major contributor to the
16 global warming impact of agricultural systems, compared to soil C sequestration
17 [3]. Except for nitrate leaching, there are few references on these effects in the
18 literature, and the patterns are again not consistent across references, and for the
19 same reasons. The time-frame over which the effects of straw removal are
20 investigated is also an issue. For instance, nitrate leaching was shown to decrease in
21 the winter following the first incorporation of wheat straw in a cropping system,
22 compared to a control with no added straw [4]. However the same tendency was
23 reversed after a few years of continued straw incorporation in another trial [5].

1 Deterministic models of C-N dynamics in soil-crop systems provide a
2 unique means of addressing the afore-mentioned issues dealing with straw removal
3 effects. They simulate the major processes governing the impacts cited [6], and
4 make it possible to single out soil, climate, and management factors through
5 scenario analysis [7]. Also, they have the potential to take local context into
6 account, which is important when assessing the environmental impacts of setting
7 up a bio-energy chain in a particular area. Secondly, the environmental assessment
8 should encompass the whole chain to address potential trade-offs along the chain.
9 Life cycle assessment (LCA) provides a comprehensive, standardised framework to
10 deal with such issues, and was already applied to straw [8, 9]. Although the results
11 are generally favourable to cereal straw compared to various fossil feedstock (coal
12 or natural gas), the methodology employed in these studies did not tackle the
13 problem of ecosystem context. For instance, they all used the average emission
14 factor of 1.25% recommended by the IPCC [10] to estimate N₂O emissions,
15 although these are known to be highly variable in time and space [11].

16 In the framework of a case-study on the potential benefits of substituting
17 natural gas with wheat straw in a bio-ethanol production plant, , we therefore set
18 out to predict the effect of wheat straw removal on the dynamics of C and N in
19 arable fields, including N losses (gaseous and leaching). The model is based on
20 CERES [12], as modified to suit French conditions [13]. The second objective of
21 this work was to use the resulting data in a LCA, and to analyze the contribution of
22 field emissions in the overall performance of the straw-based system, compared to
23 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 $3 \cdot 10^7 \text{ l yr}^{-1}$, and requires $202 \cdot 10^6 \text{ MJ}$ 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 $96 \cdot 10^3 \text{ Mg}$ (dry matter basis). Estimates of wheat straw availability around the plant resulted in a collection area of $6\,000 \text{ km}^2$ (C. Jacquin, Arvalis, personal communication). However, the studied area was extended to a wider area of ca. $22\,000 \text{ km}^2$, 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

1 weather stations along a 250 km southeast-northwest transect across the study area.
2 Table 1 gives the weather statistics for these three stations, while Table 2 lists
3 selected characteristics of the three soils. The latter comprise an orthic luvisol, a
4 redoxic luvisol, and a rendzina (FAO classification, [14]). In previous work, the
5 CERES model was tested in details against experimental data for all three soils
6 (Table 2).

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

22 The rotations and their variants were run on historical series of weather data
23 spanning the 1980-2000 time period. Crop management variables other than straw
24 removal (fertilizer application, sowing date, etc..) were set according to current

1 recommended practices in the area. A simple N balance was implemented in the
2 model to calculate fertilizer N application for winter crops.

3 **2.2 The CERES model**

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

8 CERES comprises three main sub-models. First, a physical module
9 simulates the transfer of heat, water and nitrate down the soil profile, as well as soil
10 evaporation, plant water uptake and transpiration in relation to climatic demand.
11 Water infiltrates down the soil profile following a tipping-bucket approach, and
12 may be redistributed upwards after evapo-transpiration has dried some soil layers.
13 In both of these equations, we introduced the generalized Darcy's law in order to
14 better simulate water dynamics in fine-textured soils [15]. Next, a micro-biological
15 module simulates the turnover of organic matter in the plough layer, involving both
16 mineralization and immobilisation of inorganic N. It comprises three endogenous
17 soil OM pools: microbial biomass, active humus ('humads'), and passive humus,
18 which decompose according to first-order kinetics, and partly recycle into the
19 microbial biomass. A module for predicting the emissions of N₂O via the soil
20 nitrification and denitrification pathway was recently incorporated [16]. Also, an
21 ammonia (NH₃) volatilization module was included in CERES [17]. Lastly, crop
22 net photosynthesis is a linear function of intercepted radiation according to the
23 Monteith approach, with interception depending on leaf area index based on Beer's

1 law of diffusion in turbid media. Photosynthates are partitioned on a daily basis to
2 currently growing organs (roots, leaves, stems, fruits) according to crop
3 development stage. The latter is driven by the accumulation of growing degree
4 days, as well as cold temperature and day-length for crops sensitive to vernalization
5 and photoperiod. Crop N uptake is computed through a supply/demand scheme,
6 with soil supply depending on soil nitrate and ammonium concentrations and root
7 length density.

8 **2.3 Life cycle assessment**

9 Life cycle assessment (LCA) was conducted within the framework provided
10 by the BioFit project [8], dedicated to the LCA of bio-fuels in european context.
11 The analysis comprised the bio-ethanol from wheat grains chain, along with the
12 straw for heating and triticale for CHP chains. It follows the ISO norms 14040 and
13 14041 regarding the various stages of LCA: goal and scope definition, inventory
14 analysis, impact assessment, and interpretation [9]. In our case, the functional unit
15 is one litre of ethanol, produced either using natural gas (reference system, S1) or a
16 50%-50% mix of gas and straw (alternative system, S2). The systems are depicted
17 in Figure 1, which highlights the main differences between them. In the S2 system,
18 the removal of straw results in the loss of SOM as well as nutrients, which are
19 supplemented in mineral form. The loss of nutrients is based on the chemical
20 composition of straw, while the SOM loss is a estimated with the CERES
21 simulations. Since straw is considered a by-product of wheat grain production, all
22 the emissions resulting from the cultivation of wheat are allocated to the grains [9].
23 The wheat straw is pressed into bales, transported by tractor to a temporary storage

1 on the farm, prior to being collected by trucks and transported to the bio-ethanol
2 plant. The bales are stored there for a short time and fed directly into a dedicated
3 boiler for CHP generation. The inventory of environmental outputs was based on
4 BioFit data, which was supplemented it with data from a more recent LCA based
5 on the same plant under study here [18]. Following the latter study, we used a
6 weight-based allocation ratio to partition impacts between the product of interest
7 (ethanol) and its main by-product (wheat meal for animal feed).

8 The following impact categories were analysed: depletion of natural
9 resources, global warming, atmospheric acidification, eutrophication, and potential
10 for ozone formation. The impacts were expressed in equivalent substances: carbon
11 dioxide (CO₂) for global warming, sulphur dioxide (SO₂) for acidification, nitrate
12 (NO₃⁻) for eutrophication, and ethene (C₂H₄) for potential ozone formation.

13 **3 RESULTS AND DISCUSSION**

143.1 **Field emissions and effect of straw removal**

15 **3.1.1 Effects of soil type, geographical location, climatic year and crop** 16 **rotation**

17 Prior to analysing the effects of straw removal *per se*, it is interesting to try
18 and rank the effects of the other factors included in the simulation scenarios,
19 including soil type, geographical location, climatic year and crop rotation. Among
20 them, climatic year appeared as the most sensitive factor, the other factors having a
21 similar but smaller influence on model outputs. This is illustrated on Figure 1 in the
22 case of wheat grain yields, which shows that inter-annual variability resulted in

1 standard deviations up to five times higher than those resulting from the variations
2 in crop rotation types. However, comparison with yield census data over the region
3 shows that inter-annual variation might be over-estimated by CERES. The standard
4 deviation calculated across the years from these data is indeed much lower than that
5 estimated by the crop model (Figure 1), even if the census data are likely to smooth
6 out variability because they represent regional averages as opposed to the field-
7 scale simulations provided by CERES. The latter also over-estimated the average
8 harvested yield by 10% to 35%, which is not surprising since the model does not
9 include the effect of pests and diseases, as well as grain losses upon harvest.

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

19 Regarding outputs other than crop yields, the effect of climatic location and
20 soil type may be analysed by comparing the four situations resulting from the
21 combination of the above two extreme soils (rendzina and deep loam) and climatic
22 locations (Abbeville and Fagnières). Switching from the wetter location (Abbeville)
23 to the drier one (Fagnières) with the deep loam resulted in a grain yield decrease of
24 1 Mg DM ha⁻¹, on average. Deep drainage also decreased 132 mm, which is very

1 close to the 138 mm difference in annual rainfall across the two locations (Table 1).
2 As a consequence, nitrate leaching decreased $14.6 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the drier climate
3 compared to the wetter one. Conversely, with the rendzina soil, switching to a
4 wetter climate resulted in a slight increase in grain yields ($0.3 \text{ Mg DM ha}^{-1}$), two-
5 fold higher amounts of deep drainage, and an $8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ increase in nitrate
6 leaching on average. In both soils, nitrous oxide emissions were relatively low,
7 ranging from 0.15 to $0.60 \text{ kg N-N}_2\text{O ha}^{-1} \text{ yr}^{-1}$. This was especially true for the
8 rendzina soil due to its alkaline pH, which is known to reduce N_2O production from
9 denitrification [19]. The emissions were little affected by climate, decreasing at
10 most $0.20 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ when switching to the drier climate with the deep loam.
11 Ammonia volatilisation increased 80% in the drier climate relative to the wetter
12 one, whether with the deep loam or the rendzina soil.

13 CERES predicted a net increase in soil organic matter all soils, even when
14 straw was removed most of the years. The variations in SOM were very similar
15 across climates, and ranged from 0.15 to $0.75 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, with the exception of
16 the rotation involving grain maize for which the increase was much higher, ranging
17 from 1.0 to $1.3 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. These values fall in the higher part of the -2.0 to 2.0
18 $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ range reported for arable soils in the area over the 1970-1998 time
19 period [20], regardless of crop rotations and straw management.

20 **3.1.2 Effect of straw removal frequency on model outputs**

21 Figures 3 and 4 show the effects of crop rotation and straw removal
22 frequency on various model outputs for the two extreme combinations of soil and
23 climate: the rendzina at Fagnières and the deep loam at Abbeville. The differences

1 across rotations are generally more important than those related to straw
2 management for a given rotation. The removal of straw thus bore little effect on
3 field emissions. The highest effects were noted on crop productivity, with grain
4 yield being negatively affected by straw removal because of a lower net
5 mineralisation of N in soils. The yield losses ranged between 0.05 to 0.15 tons DM
6 ha⁻¹ for each ton of straw removed, which is in line with the 0.13 Mg grain DM ha⁻¹
7 loss reported for various crops in the US [2]. This corresponds to a straw fertiliser
8 value ranging from 1.5 to 4.5 kg N Mg⁻¹ straw, which is lower than the total N
9 content of the straw, estimated at 6 kg N Mg⁻¹ straw DM [21]. Harvested straw
10 yields paralleled grain yields, and varied between 1.0 and 4.6 Mg straw DM ha⁻¹
11 when averaged over the whole rotation (Figure 3, middle).

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

22 Similarly to nitrate leaching, N₂O emissions decreased slightly with
23 increasing straw removal, with a rate of 0.1 to 0.25 kg N Mg⁻¹ straw DM (Figure 4,
24 top). There is little information on such effect in the literature, but the available

1 results generally emphasize the links with N fertilization: straw return to soil
2 increases to soil's denitrification potential, and to a some extent its capacity to
3 produce N₂O [25], but decrease it temporarily in case the incorporation of straw is
4 followed by an application of mineral or organic fertilizers [26, 27]. This was
5 however not the case here. Nitrous oxide emissions were converted in CO₂
6 equivalent using a global warming potential of 270, which corresponds to a 100-yr
7 projection [28]. They were subsequently aggregated with the C balance of the soil
8 to estimate the net impact of the cropping system on global warming. Straw
9 removal contributed to increase the global warming impact in both locations
10 (Figure 3, top), by one Mg equivalent CO₂ ha⁻¹ on average, due to the contribution
11 of incorporated straw to SOM in the long-term. Over the 30-yr simulation period,
12 the model simulated a sequestration potential ranging from 0.05 to 0.1 Mg C Mg⁻¹
13 of added straw DM, being lowest for the SB-WW-WW rotation in Fagnières. These
14 figures are in the higher range of the values reported in a recent review [29],
15 namely a range of 0.01 to 0.04 Mg C Mg⁻¹ straw DM. Wilhem et al. [2] cited a
16 much broader range (0.0 to 0.1 Mg C Mg⁻¹ straw DM), but noted a major
17 interaction with tillage. Here, the type of rotation was also decisive as regards the
18 sequestration capacity of the cropping system, whether the wheat straw was
19 removed or not. The rotation involving grain maize has the highest sequestration
20 potential because of the high level of residue return from the maize crops.

21

22 Ammonia volatilisation correlated negatively with the rate of straw removal
23 in Fagnières, and positively in Abbeville (Figure 4, bottom). These two opposite
24 cases reflect different balances between the two factors which could explain the

1 effect of straw management on NH_3 volatilization: on the one hand, incorporating
2 straw in soil increases its capacity to immobilize mineral fertilizer N, and thus
3 decreases the availability of ammonium to volatilization; on the other hand, straw
4 incorporation increases the net mineralization of nitrogen, being produced in the
5 ammonium form, which is likely to increase NH_3 volatilisation. However, as
6 observed after application of urea [30], straw management had little effect on
7 volatilization. The maximum differences between the treatments with total straw
8 return to soil and straw removal ranged from 1 to 2 kg N- NH_3 ha⁻¹ yr⁻¹ in Fagnières,
9 representing only 5 à 10% of the absolute emissions, and these deviations were
10 similar in Abbeville except for two rotations.

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

17 **3.2 Life cycle assessment**

18 For the purposes of the LCA, we selected one crop rotation which was
19 judged representative of the other rotations, namely the WOR-WW-WW rotation.
20 Table 3 summarises the direct emissions data simulated by CERES for the two
21 extreme soil and climate combinations (the rendzina soil in Fagnières and the deep
22 loam in Abbeville), averaged over time. The main differences between the two soils
23 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 $15 \text{ MJ kg}^{-1} \text{ DM}$. 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

1 operate the straw boiler was 20 times lower than the natural gas savings incurred by
2 the use of straw (Figure 5).

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

20 **3.3 Conclusions**

21 Using the framework of life cycle assessment, we evaluated the interest of
22 substituting cereal straw for natural gas for combined heat and power generation in
23 a bio-ethanol plant. As already shown in previous studies, the main benefits lied in

1 the saving of non-renewable resources and the reduction of greenhouse gas
2 emissions, which proved very efficient. The picture was mitigated regarding other
3 impacts such as eutrophication or acidification, whose outcome actually depended
4 on local ecosystem context (ie, soil type and climatic zone). The use of a
5 biophysical model made it possible to take such factors into account, substantiating
6 the idea that impacts occurring on a local scale should be addressed based on local
7 characteristics rather than on national or global averages. This will ultimately mean
8 that some biomass production zones will emerge as performing better than others,
9 from the point of view of environmental impacts, and thus induce some kind of
10 spatial differentiation with respect to the implementation of biomass chains.

11 Although this idea is rather intuitive, it had not been implemented yet in life cycle
12 assessment. The use of biophysical models may therefore be expected to play a
13 crucial role in the future development of this methodology.

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

22

1 **4 ACKNOWLEDGEMENTS**

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

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14

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

3

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

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

4

Soil classification	Selected properties				Reference
(FAO)					
	Topsoil texture	pH	%C	%CaCO ₃	
	(UDSA triangle)				
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]

5

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 N₂O, converted to CO₂ based on a global warming power of 270. The contribution of N₂O is singled out.

Location	Global warming impact		Ammonia	Nitrate leaching	Crop yield	
	N ₂ O part				Grains	Harvested straw
	kg eq. C-CO2 ha ⁻¹		kg N-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

1 **Figure captions**

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

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

14 **Figure 3.** Effect of straw removal frequency on the emissions of N₂O (top),
15 nitrate (middle), and ammonia (bottom) in the rendzina and deep loam soils, for the
16 various rotations (WOR-WW-WW: ●; WOR-WW-WB: ○; SM-WW: ▲; GM-
17 WW:△; SB-WW-WW: ■; SB-WW-WB: □; wheat mono-culture: ◇). The solid lines
18 are linear regressions against straw removal frequency for each rotation. Note the
19 differences in scales for the y-axis between the two soils.

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

1 WW-WB: □; wheat mono-culture: ◇). The solid lines are linear regressions against
2 straw removal frequency for each rotation. The GHG balance, expressed in
3 equivalent CO₂ net emissions, compounds two items: N₂O emissions, and soil
4 carbon content variations.

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

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Figure 1

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Figure 2

Figure 3

Figure 4

Figure 5