Front. Agr. Sci. Eng. 2022, 9(2): 284–294 https://doi.org/10.15302/J-FASE-2021435

RESEARCH ARTICLE

AGRI-ENVIRONMENTAL ASSESSMENT OF CONVENTIONAL AND ALTERNATIVE BIOENERGY CROPPING SYSTEMS PROMOTING BIOMASS PRODUCTIVITY

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KEYWORDS

alternative cropping systems, bioeconomy, biogas, biomass production, fertilization autonomy, greenhouse gas assessment

HIGHLIGHTS

- Agri-environmental assessment of food, feed and/or biogas cropping systems (CS).
- Four-year experiment for the agri-environmental assessment of two innovative CS.
- Biogas CS has equal soil returned biomass than food CS but higher exported biomass.
- Feed and biogas CS present higher biomass productivity, but higher CO_2 emissions.
- CO_2 emissions related to produced biomass are 26% (±5%) lower in biogas CS.

Received October 1, 2021;
Accepted February 10, 2022.

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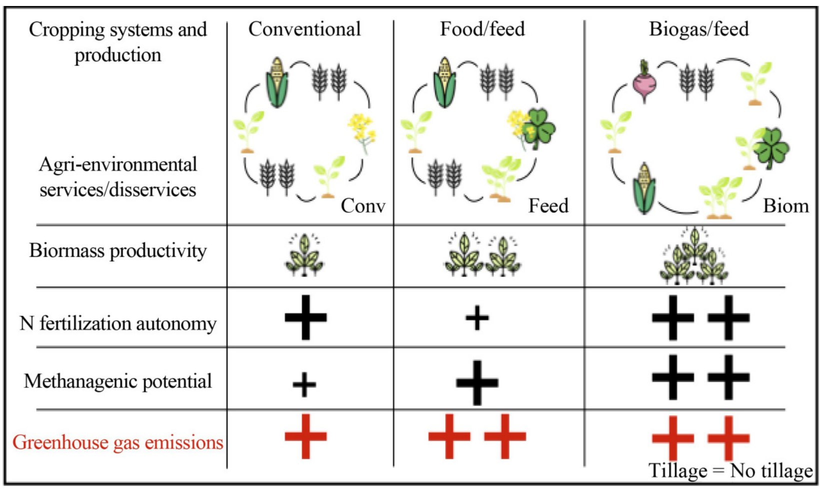
GRAPHICAL ABSTRACT



ABSTRACT

Bioenergy, currently the largest renewable energy source in the EU (64% of the total renewable energy consumption), has sparked great interest to meet the 32% renewable resources for the 2030 bioeconomy goal. The design of innovative cropping systems informed by bioeconomy imperatives requires the evaluate of the effects of introducing crops for bioenergy into conventional crop rotations. This study aimed to assess the impacts of changes in conventional cropping systems in mixed dairy cattle farms redesigned to introduce bioenergy crops either by increasing the biomass production through an increase of cover crops, while keeping main feed/food crops, or by substituting food crops with an increase of the crop rotation length. The assessment is based on the comparison between conventional and innovative systems oriented to feed and biogas production, with and without tillage, to evaluate their agri-environmental performances (biomass production, nitrogen fertilization autonomy, greenhouse gas emissions and biogas production). The result showed higher values in the biogas cropping system than in the conventional and feed ones for all indicators, biomass productivity (27% and 20% higher, respectively), nitrogen fertilization autonomy (26% and 73% higher, respectively), methanogenic potential (77% and 41% higher, respectively) and greenhouse gas emissions (15% and 3% higher, respectively). There were no negative impacts of no-till compared to the tillage practice, for all tested variables. The biogas cropping system showed a better potential in terms of agri-environmental performance, although its greenhouse gas emissions were higher. Consequently, it would be appropriate to undertake a multicriteria assessment integrating agri-environmental, economic and social performances.

1 INTRODUCTION

Over the last decade, increased focus on the concept of a bioeconomy has sparked interest as an alternative to fossil-based economy[1,2]. A bioeconomy consists of using renewable biological resources to produce food, materials and energy while mitigating climate change and managing natural resources. As a low carbon economy, a bioeconomy predominantly relies on biomass that is considered as the single source of renewable and natural C present in sufficient quantity to be substitutable for fossils fuels and capable of providing human needs while storing C to reduce global warming[3]. A bioeconomy requires diversification of cropping systems to develop innovative production systems by integrating food, feed and/or energy, enhancing biomass productivity and mitigating impact on biodiversity, natural resources and climate change.

In this context, energy-efficient crops are increasingly integrated into food and feed cropping systems with a high biomass productivity, where agroecological practices are associated with biogas production[4,5]. Indeed, being a versatile and storable source of C, biogas (methane-based gas mixture produced by the anaerobic digestion of biomass) is seen to have a key role in the development of such a low carbon economy[6]. Compromises between the different uses of biomass (food, feed and biogas) and the impacts of these cropping systems on climate change mitigation and natural resources need a deeper understanding. With the expansion of cropping systems maximizing biomass productivity, number of studies have focused on the effects of these systems on ecosystem processes (e.g., nitrogen cycling dynamics and greenhouse gas emissions) in order to identify the ecosystem services but also the disservices associated with those systems[7–10]. Also, bioenergy crops were found to enhance soil fertility and could result in lower N inputs as long as crop residues are retained in the soil, due to great N uptake by the plants[11–13]. However, studies have investigated the N fertilization autonomy of bioenergy crops at the system scale by focusing on one or two crops rather than on the entire crop rotation. In addition, most studies have focused on the greenhouse gas emissions of particular crops, identifying which crops would be more efficient in terms of lower emissions but the whole effect at a crop rotation scale has not been sufficiently considered[14–17].

Although the integration of bioenergy crops into crop rotations is at the heart of bioeconomy systems, it has been postulated that the integration of perennial crops would have greater impacts in terms of soil C sequestration, N cycling and biomass yields[10,18]. In terms of greenhouse gas emissions, perennial crops gave a decrease of 102% (±12.5%) whereas annual crops reduced greenhouse gases emissions by 50% (±10%)[14,15,19]. However, perennial crops can also present negative trade-offs between the productivity and non-marketed ecosystem services, such as the invasiveness of some species, their water uptake, and the spread of pests and pathogens[20]. Due to their longevity, a competition between the crop types would appear as it will not be possible to use them both as food and as feed, according to the climate and/or the needs of the different agricultural sectors, depending on the year. A limitation of the studies on the evaluation of the sustainability of bioenergy cropping systems stands in the number of the variables considered, as they are usually limited and do not cover the entire production chain to evaluate efficiently the trade-offs and impacts of bioenergy cropping systems. In addition, when developing bioenergy cropping systems, most of the practices are applied to the production of perennial crops, often monocultures of miscanthus, sugarcane, sweet sorghum or switchgrass, rather than diversified crop rotations[18,20–23]. Using conservation agriculture practices could enhance the production of bioenergy crops, using diversified crop rotations instead of perennials, with maximized ecosystem services, such as the limitation of soil disturbance with the limitation of tillage and a constant soil cover with alternation of the vegetation types[24,25]. As an example, no-till practice enhances soil quality and health, limiting greenhouse gas emissions without negative impacts on the biomass productivity in bioenergy crops[21,25,26].

Deepening understanding of the long-term effects of high biomass productivity cropping systems using a system-scale approach is pivotal to warrant the successful integration of annual crops in diversified crop rotations. This study examined the effects of high biomass productivity cropping systems on environmental and agronomic services to assess their sustainability at the system scale. We also investigated tillage and no-till in this experiment to assess the potential effects of tillage practices on system performances. The agri-environmental services studied were: (1) biomass productivity and soil returned biomass; (2) N fertilization autonomy; (3) methanogenic potential; and (4) greenhouse gas emissions. From an agronomic point of view, we hypothesized that biogas cropping systems (biomass production for feed and/or biogas) would show a higher biomass productivity due to the higher diversity and number of crops in the rotation. The cropping systems that are more productive would returned more biomass to the soil and have the best agri-environmental performances. It was also hypothesized that the no-till practice would have no negative impacts on the evaluated services.

2 MATERIALS AND METHODS

2.1 Experimental site and design

The study was conducted over three years from 2016 to 2019 at the UniLaSalle Polytechnic Institute farm (49°27′59″ N, 2°4′21″ E) in Beauvais, France. The climate is oceanic/temperate, with 10.7 °C average annual temperature and 660 mm average annual rainfall. The soil was characterized by 17.1% clay, 13.4% sand, 68.8% silt, 1.8% organic matter and alkaline pH. The field was divided into 26 individual plots, each measuring 24 m × 85 m, grouped into four blocks representing a different year in the crop rotation (Fig. 1). The experimental design comprised three cropping systems conducted under two tillage practices (i.e., with and without tillage).

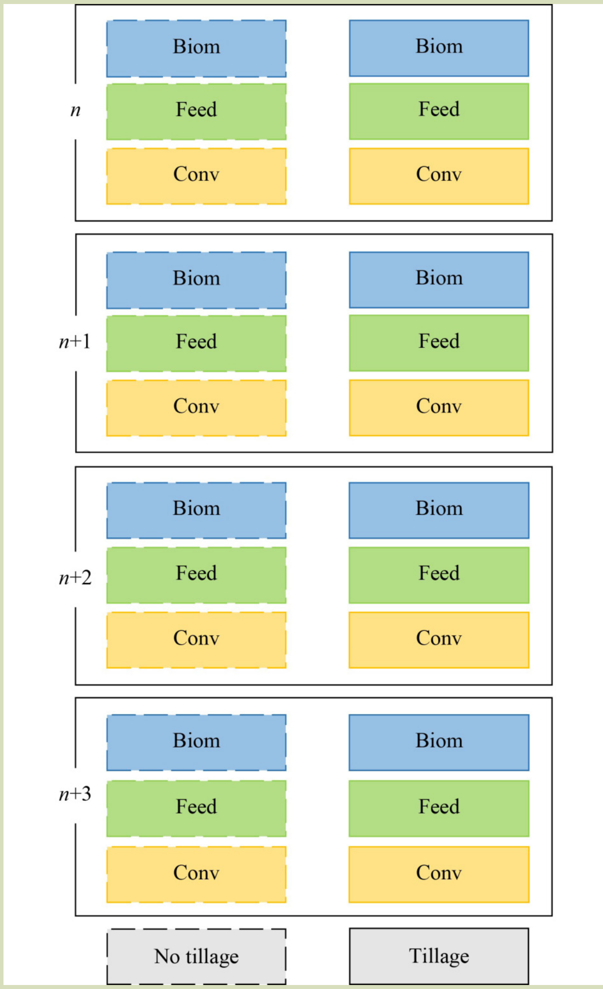


Fig. 1 Experimental design of the study site, locating the conventional cropping system (Conv), the feed cropping system (Feed) and the biogas cropping system integrating high biomass productivity (Biom), as well as the tillage and no tillage treatments.

The first system was referred as “conventional cropping system” (Conv) and was composed of six stages in its rotation (Fig. 2A), representing a typical crop rotation (mixing food and feed crops) from a dairy cattle farming system in northern France. Manure, slurry and cover crops residues were incorporated into the soil as fertilizer during the crop rotation. The straw from the first soft wheat crop in the rotation was exported but for subsequent soft wheat crops, the straw was chopped and retained on the field.

The second system, called “feed cropping system” (Feed), was a transitory system that promotes food and feed productions and includes cover crops that can be exported for feed or biogas production (Fig. 2B). Fertilization in this system consisted of amending the soil with liquid digestates, residues from biogas production. Depending on the tillage practice, the species used as cover crops in the rotation slightly changed to ensure a permanent plant cover for both practices.

The third system, “biogas cropping system” (Biom), was a high biomass productivity system, with the biomass exported for feed and biogas production and comprised seven stages in its crop rotation (Fig. 2C). Biogas liquid digestates were incorporated into the soil during the rotation to ensure an input of nutrients for the crops.

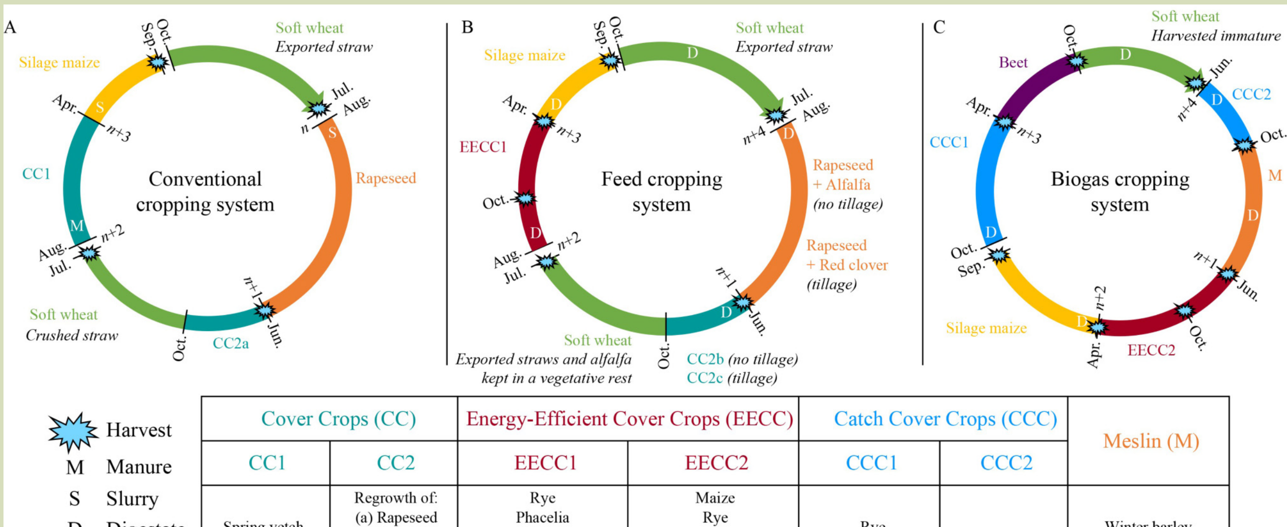
2.2 Biomass productivity

The biomass was sampled at each harvest, using a 1-m^2 quadrat for the cover crops, wheat, rapeseed and meslin (i.e., immature mixed legume and cereal crops). The non-harvested cover crops (CC1 and CC2; Fig. 2) were sampled in November at their optimum growth. Silage maize and forage beet were sampled differently than the other crops, due to the spacing between the rows and crops. Two adjacent rows of maize were removed along a 3-m transect and four rows of forage beet along a 4-m transect. For all the crops, sampling was undertaken three times per plot using a systematic diagonal pattern. All the plants were cut at 10 cm above the soil surface, except for forage beet, which was completely exported and separated at the collar to determine the aboveground biomass. The biomass was then oven-dried at 65 °C for 96 h. Due to the sugar content of forage beet, there were two steps in the drying process for this crop: (1) 40 °C for 4–7 days, depending on if the root was dried and (2) 75 °C for 72 h. The weighted dry-mass was used to determine the biomass productivity of each crop, which were then added for a same crop rotation to calculate the biomass productivity (t·ha^{-1} DM) at the system scale.

2.3 Nitrogen fertilization autonomy assessment

2.3.1 Plant sampling methods to measure the N content

The 10 cm of biomass left after harvest (except for the forage beet), constituted in a small intake of organic matter in-between each crop. The overall biomass of the cover crops (CC1 and CC2) was also incorporated into the soil, for Conv and Feed. The nutrient exported into the biomass was measured at each harvest, or in November for the non-harvested cover crops. The C and N contents were measured for the 10 cm high biomass left and for the above 10 cm biomass harvested. For the cover crops, wheat, rapeseed and meslin, a 300-g sample per plot was used for analysis and 10 plants were used for the maize at both heights. For the forage beet, the leaves and roots were separated and C and N contents were analyzed for the leaves, using 600 g of leaves from 20



Cover Crops (CC)		Energy-Efficient Cover Crops (EECC)		Catch Cover Crops (CCC)		Meslin (M)
CC1	CC2	EECC1	EECC2	CCC1	CCC2	
Spring vetch Phacelia Oat	Regrowth of: (a) Rapeseed (b) Rapeseed and alfalfa (c) Rapeseed and red clover	Rye Phacelia Italian ray-grass Red clover* Spring vetch* Winter horse bean*	Maize Rye Italian ray-grass Winter horse bean* Winter vetch* Red clover*	Rye Winter fodder pea Winter horse bean	Rapeseed Ryegrass	Winter barley Winter fodder pea Winter vetch

*Harvested in April

Fig. 2 Detailed crop rotations of each tested cropping systems, integrating the harvested time and the amendment type for each crop. Reprinted from Denier et al.[26], with permission from Elsevier.

plants and their roots as 1 kg of cut roots in cubes. More details on the protocols of the measures and analysis are given in supplementary material (Fig. S1).

2.3.2 N input and biomass output calculations to determine N autonomy

Fertilization was made using manure and slurry for Conv, and digestates were used for Biom and Feed (Fig. 2). Each manure, slurry and digestate input used in the cropping systems was analyzed to measure the N concentration. The N inputs were calculated using the amendments used in the field, as well as the quantity of N included in the biomass returned to the soil. The returned biomass was composed of the first 10 cm above the ground in all cropping systems, the forage beet leaves in Biom and the entire aboveground biomass of non-harvested cover crops (CC1 and CC2) in Conv and Feed. The N concentration in those parts was multiplied by the respective dry biomass quantity (dried at 60 °C for 48 h) to obtain the total N content for the biomass produced. This value was added to the amount of N added with the amendments to evaluate the total N input (kg·ha^{-1}) to the soil for the entire crop rotation. The N mineralized in the soil or added in rain were included in the calculations.

The exported N in the crop rotation comprised the N content in the exported biomass, which included all the harvested biomass produced above 10 cm in all cropping systems (maize, wheat and rapeseed straws, CCC, meslin and EECC), the grains for rapeseed and wheat in Conv and Feed and the beet roots in Biom. Just as the returned N from the biomass, the total exported N was calculated from the N concentration in the exported biomass multiplied by the biomass productivity for each crop. Then, each crop N value was summed to represent the total N exported (kg·ha^{-1}) from an entire crop rotation.

Once the N input and output values were calculated for the entire crop rotation, an index of the N balance was estimated by subtracting the total N input by the total N output for each cropping system and tillage/no tillage conditions. To evaluate the N fertilization autonomy, the total N input, including the amendments and the N in the returned biomass, was divided by the total N exported from the biomass, separating the tillage and the no tillage conditions. The relation between the N in the returned biomass and the total N exported from the biomass was calculated.

2.3.3 Soil residual N measurements

The soil residual N was measured at the beginning and end of winter. Six samples were taken along a transect across the width of the plot in December 2016. This transect started 7 m from the edge of the plot for the first residual N samples. For the next sampling in February 2017, the transect started 8 m away from the edged and was moved down a further 1 m for each subsequently sampling. Six samples along the transect were taken, separating the soil into four depths (0–30 cm; 30–60 cm; 60–90 cm and 90–120 cm) that were then pooled. Four samples were taken per plot (1 per soil horizon) and sent to an external laboratory for analysis of residual N. The soil residual N was calculated by adding the residual NO_3-N and NH_4-N concentrations which were determined by colorimetry after 1 mol·L^{-1} KCl extraction[27].

2.4 Methanogenic potential

Each crop was analyzed to measure their methanogenic potential (i.e., the maximum quantity of methane produced by a plant; NL CH_4 kg·DM^{-1}), using samples from the fresh biomass above 10 cm. For the cover crops, wheat, rapeseed and meslin, a sample of 2 kg was collected for the analysis; and 10 plants were sampled for maize and 1 kg of sliced roots for forage beet. More information on the sampling methods can be found in supplementary material (Fig. S1). The analyses were performed using a standard method[28]. Duplicate plant samples were added to a 500-mL glass bottle that contained anaerobic sludges used as inoculum. A bottle filled with only the sludge was used as a control. The bottles were then shaken in an incubator at 35 °C. The methanogenic potential of each cropping system was calculated using the weighted methanogenic potential by the biomass productivity of each crop, which were then summed to obtain the methanogenic potential at the system scale.

2.5 Greenhouse gas assessment

The greenhouse emissions were modeled using the ABC'Terre tool[29], based on five variables. For the first variable (i.e., direct emissions due to fertilizers and biomass inputs in soils), the input parameters were classified into two main categories: (1) the direct N_2O emissions in the field due to soil management of N inputs (including the mineral nitrogen inputs, the organic waste products inputs, the crop residues and the cover crop residues); and (2) the direct CO_2 emissions due to lime and urea inputs. The second variable focused on the indirect N_2O emissions due to N inputs, and more specifically on the (1) leaching of total N inputs; (2) volatilization of N from mineral inputs; and (3) volatilization of N from organic inputs. As the third variable, the emissions from the use of farming machinery were calculated. The emissions included were from (1) mineral and organic fertilization, as well as other inputs; (2) tillage; (3) soil working other than tillage; (4) harvest; (5) sowing; (6) treatments; (7) management of cover crops; and (8) pressing. The fourth variable used in the model was the emissions from the inputs before their use in the field and including induced emissions from the treatment (e.g., mineral nitrogen input including production, transportation and fuel; organic waste products transportation and treatment; P-K-$CaCO_3$ inputs; and seeds including main crops and cover crops). Finally, the fifth variable represented the emissions from the carbon stock variation (sink or source) over a 30-year period, using the tool SIMEOS-AMG, based on the AMG model[30]. Input data of this tool included climate, soil, tillage, crop management, cover crops and, soil amendments.

However, the ABC'Terre tool does not consider the emissions from (1) livestock farming (e.g., cattle, buildings, inputs such as feed and medicines, livestock effluents production and storage for biogas) and (2) the postharvest (e.g., yield transportation, storage, and transformation).

2.6 Data analysis

To identify differences between each cropping system and between the tillage/no-till conditions, two-way ANOVAs were computed for the variables as the normality hypothesis was validated. When differences were highlighted by the two-way ANOVA, Tukey post-hoc tests were performed to identify precisely the significant differences between the conditions. PERMANOVA tests were performed on the soil residual N data, as the assumptions for ANOVA were not respected, in order to identify differences between each cropping systems and the tillage/no-till conditions. All statistical analyses were computed using the packages "car", "vegan" and "stats" in R-Studio (version 4.0.2).

3 RESULTS AND DISCUSSION

3.1 Contrasting biomass productivity among cropping systems

Irrespective of the cropping system, tillage practice did not affect any of the tested biomass categories (Fig. 3). In contrast, total, returned and exported biomasses were significantly affected by the cropping system type. Total biomass productivity in Biom was higher than in the other two systems (Fig. 3A) while the returned biomass was lower in Feed than in Biom and Conv (Fig. 3B) and the exported biomass was higher

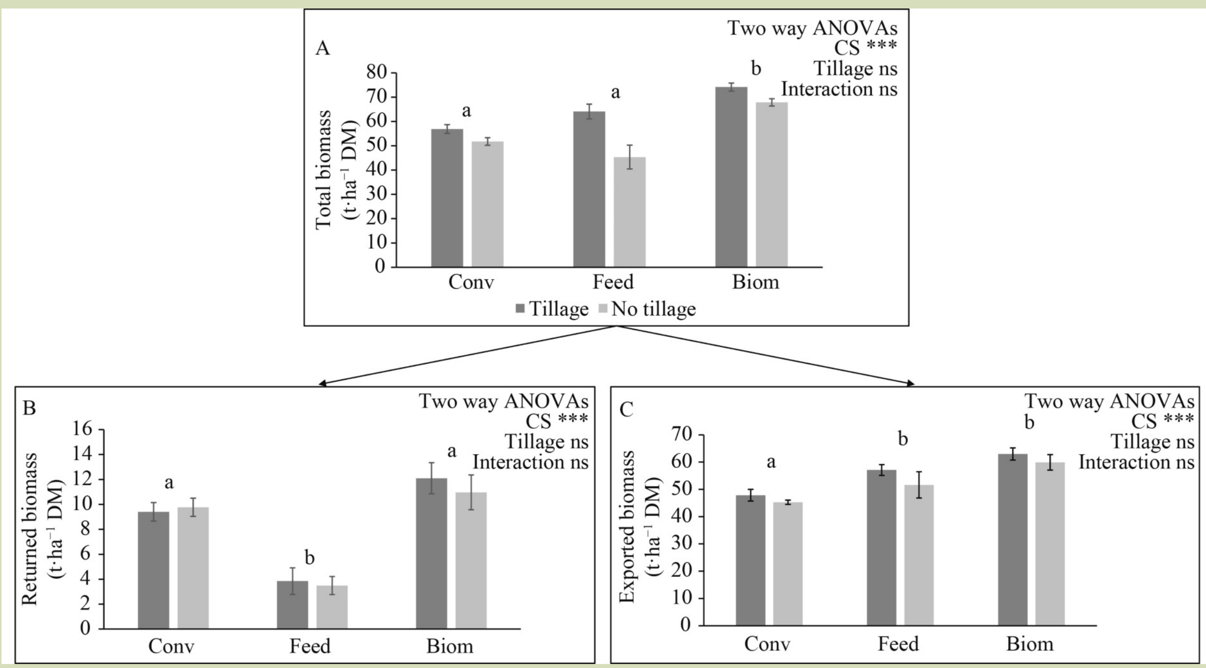


Fig. 3 Differences between each cropping system under tillage/no tillage conditions within a full crop rotation (4 years) for the total aboveground biomass productivity (A); returned aboveground biomass (B); and exported biomass (C). The bars represent the mean ± standard error. The letters represent the significant differences between each cropping system according to Tukey post-hoc tests. The significance level "ns" means not significant.

in Feed and Biom compared to Conv (Fig. 3C).

Greater returned biomass to soil as observed for Biom could have a positive impact on soil properties, functions and ecosystem services (e.g., soil biodiversity by improving food quantity and web, soil organic carbon, and thus, soil fertility)[26,31,32]. Overall, these results confirm the interest to design highly productive biogas cropping systems with an important crop residual restitution.

3.2 Nitrogen fertilization autonomy

Tillage practice had no effect on any of the tested variables linked to the N fertilization autonomy and the soil residual N. Unlike the tillage practice, exported N was significantly affected by the cropping system type, with Biom and Feed showing higher amounts of exported N than Conv (Fig. 4A), which can be explained by their higher exported biomass. Biom showed a higher returned N quantity than the other cropping systems (Fig. 4B). To determine N fertilization autonomy efficiency a focus was put on the quantity of N input from the returned biomass to the soil, which was similar for each cropping system (Fig. 4C). There were differences between the cropping systems for the relation between the returned N and the exported N in the biomass, Feed showing a lower ratio than the other two systems (Fig. 4C). In contrast, soil residual N was similar for each cropping system, either at the beginning or at the end of winter (Table 1).

Although Biom had a greater amount of exported N, due to its higher exported biomass, it also had a greater amount of returned N than Feed and Conv. This is likely to be due to the higher proportion of N-rich crop residues as well as the use of digestate inputs in Biom compared to Feed and Conv. Even if fertilization autonomy was not reached, the system with maximal biomass production including crops for biogas (Biom) was more efficient in nitrogen economy. Indeed, the efficiency of bioenergy crops in terms of enhancing soil fertility by returning more biomass into the soil has been highlighted due to the high N uptake of these plant species, although studies focused on the crop scale[11,13]. In the present study, the biogas cropping system was equivalent to Conv when considering at the ratio of returned to exported N, highlighting that even if most of the biomass is exported in this system, there is no negative impact on the returned quantity, which could allow for a better autonomy potential.

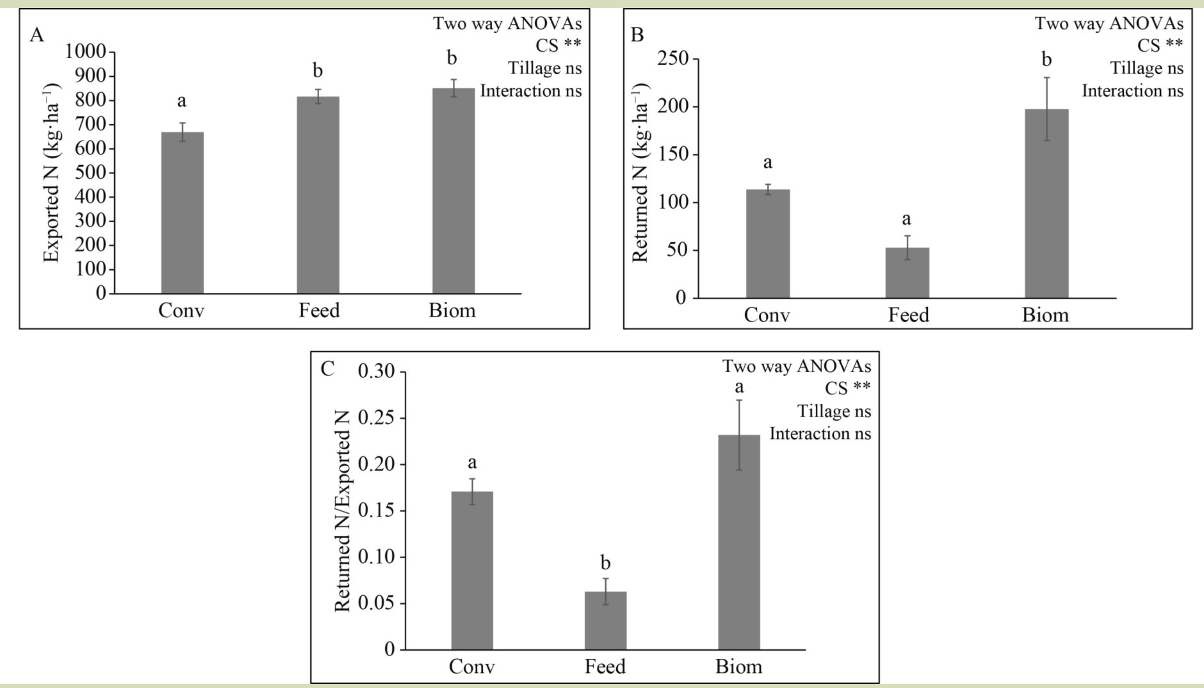


Fig. 4 Differences between each cropping system within a full crop rotation (4 years) for the exported N quantity in the biomass (A); the returned N quantity in the biomass (B); the relation between the returned N (from crop residues) and the exported N quantities in the biomass (C). The bars represent the mean ± standard deviation. The letters represent the significant differences between each cropping system according to Tukey post-hoc test. The significance level "ns" means not significant.

Table 1 Mean values of the soil N residual (kg·ha^{-1} (mean ± SE)) at the beginning and the end of winter for each cropping and tillage/no tillage conditions

Time	Cropping system type	Tillage	No tillage
Beginning of winter	Conv	57.9±8.11	52.4±7.34
	Feed	74.6±10.1	53.3±8.35
	Biom	61.9±6.49	70.7±12.1
End of winter	Conv	72.4±9.77	61.9±5.39
	Feed	82.9±16.9	67.1±8.21
	Biom	66.6±8.15	70.1±10.1

3.3 Methanogenic potential

The analysis on the methanogenic potential showed significant differences between each cropping systems, with a highest methanogenic potential for Biom; three and two times higher than Conv and Feed, respectively. This higher methanogenic potential of Biom can be explained by its higher biomass productivity but also the biochemical characteristics of crops driving biomass degradability (i.e., legume species in mixed immature forage crops) and associated to high energy content (lipid and sugar)[33]. In the present study, forage beet and immature wheat that are rich in sugar/starch (like first-generation ethanol) conferred on the high biomass productivity cropping system an important methanogenic potential leading to a higher potential biogas production.

3.4 Greenhouse gas emissions

Total greenhouse gas emissions were significantly lower in Conv than in the other two cropping systems (Fig. 5A). Lower eqCO_2 in Conv can be explained by lower N fertilizer inputs, organic amendments, mineralization N input, machine interventions for the sowing and harvest (e.g., unharvested cover crops), as well as the legume species frequency and abundance. Higher eqCO_2 of biogas cropping system (Biom, including feed and biogas crops) would be explained by an important legume frequency and machine interventions given the higher number of crops with a short growing season. However, greenhouse gas emission of cropping systems should be determined according to the biomass productivity and not only on per unit area bases for comparing efficiency of systems with different production services (food, feed and biogas)[34,35]; our simulations considered the emissions for the production and harvesting, but not the valorization of the biomass. When focusing on the greenhouse gas emissions per unit mass of dried biomass produced, significantly lower emissions were observed in Biom than in Conv and Feed (Fig. 5B). Consequently, it would be appropriate to determine the long-term C balance by modeling in order to discuss and conclude its effect on climate change.

3.5 Agri-environmental assessment to determine the sustainability of cropping systems

This system-scale agri-environmental analysis revealed higher values for each of the studied services in Biom than in the other two cropping systems (Fig. 6). Feed had higher biomass

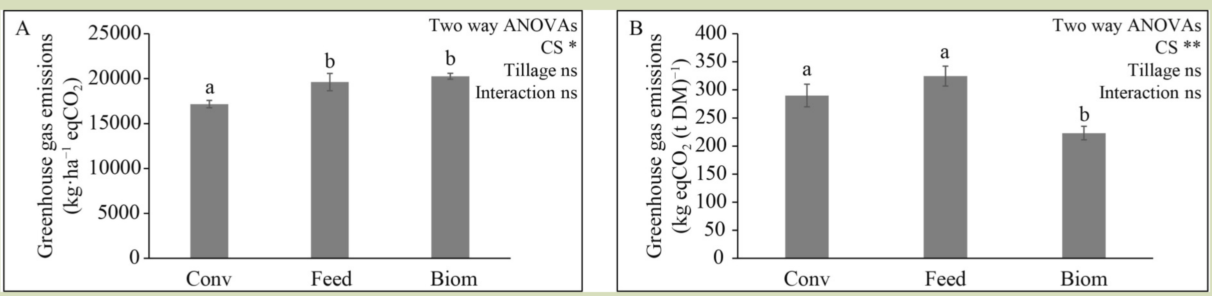


Fig. 5 Differences between each cropping system within a full crop rotation (4 years) for the total greenhouse gas emissions (A); and the greenhouse gas emissions per ton of dried biomass produced (B). The bars represent the mean ± standard deviation. The letters represent the significant differences between each cropping system according to Tukey post-hoc tests. The significance level “ns” means not significant.

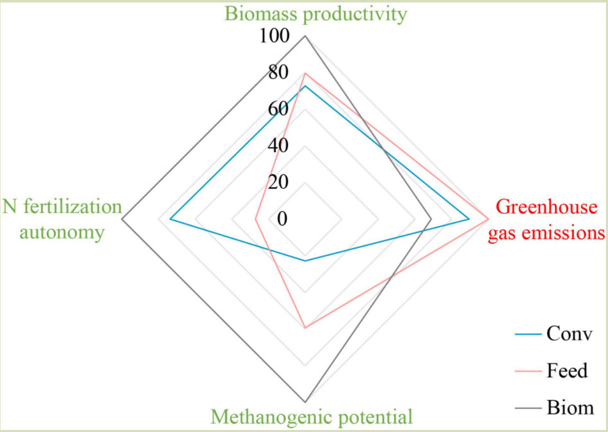


Fig. 6 Agri-environmental assessment identifying the relative part of each cropping system for the four main services (green) and disservices (red)–biomass productivity (overall productivity at the crop rotation level), N fertilization autonomy (relation between the N returned and N exported, both from the biomass), methanogenic potential (weighted with the biomass productivity for each crop and reported at the system level) and greenhouse gas emissions (total emissions per hectare for the overall system).

productivity, greenhouse gas emissions and methanogenic potential than Conv, whereas Conv had higher N fertilization autonomy than Feed. Biom offered most of the production services (biomass productivity, biogas and N fertilization autonomy) while improving soil biological activity under no tillage conditions (earthworm abundance and biomass, as well as soil microbial functional diversity) due to the high biomass restitution to the soil[26]. Its impact on climate change could be assessed for a long-term timescale by modeling the C balance (C emissions and soil carbon sequestration), at 10 and 20 years. Additionally, by integrating the biomass valorization processes into the modeling of the greenhouse gas emissions, biogas cropping systems emissions could be balanced by biogas production. Indeed, it was shown that the integration of bioenergy crops into the cropping system offset the greenhouse gas emissions by biogas production, whereas conventional cropping system had higher emissions[36]. Integrating a life cycle assessment of the cropping systems, including the biomass valorization processes depending on the sectors, would provide a deepened understanding of the overall environmental impacts of the systems at the sector scale[14,37,38]. This agri-environmental assessment showed that biogas cropping systems can be sustainable, provided the thresholds are defined for the valorization components of food, feed and biogas to avoid competition between the food and the bioenergy sectors. In contrast to perennial crops, integrating annual crops into biogas cropping systems would have little impact on arable land use. Positive biogas cropping system effects could compensate for negative indirect land use change[38]. Also, according with climate conditions of year, food and feed valorizations could be prioritized for farmer security.

4 CONCLUSIONS

This first investigation to assess cropping systems integrating food, feed and/or biogas crops has allowed quantify of their agronomic and environmental services and characterize their sustainability at a system scale. The biogas cropping system offered most production services (biomass productivity, methanogenic potential and N fertilization autonomy) but had higher greenhouse gas emissions that were not mitigated under the no tillage condition, which is in contrast what was originally hypothesized. Although, when emissions were related to biomass yield, the biogas cropping system gave lower greenhouse gas emissions than the other systems. Integrating the C balance, and notably soil organic C and C sequestration, into the results would provide a better understanding of the impacts on climate change at a longer time span. This system-scale approach showed the sustainability of the biogas cropping system which also depends on the objectives of the farming system. The multiple crop valorizations in the food, feed and bioenergy sectors could avoid competition between the food and the non-food sectors provided that supply thresholds for each bioeconomy sectors are established. Consequently, it would be appropriate would be to undertake a multicriteria assessment of innovative bioenergy cropping systems using agri-environmental, economic and social performances. Also, a life cycle assessment may efficiently compare conventional systems with bioenergy crops and unravel the overall services/disservices within a supply chain or an agricultural region.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2021435 contains supplementary material (Fig. S1).

Acknowledgements

This study was a part of the project "Bioeconomy Demonstrator Network" ("Réseau de sites démonstrateurs IAR" in French) funded from 2015 to 2020 by the European Union (ERDF), the French State (Commissariat Général à l'Egalité des Territoires, CGET) and the "Hauts-de-France" Regional Council. We thank Benoit Detot (UniLaSalle), Olivier Rey (UniLaSalle), Vincent Hervé (UniLaSalle) and Virginie Metery (Chambre Régionale d'Agriculture des Hauts-de-France) for technical assistance and the experimental design; and Lucile Godart and Hélène Zub-Preudhomme for the project coordination.

Compliance with ethics guidelines

Léa Kervroëdan, David Houben, Julien Guidet, Julia Denier, Anne-Maïmiti Dulaurent, Elisa Marraccini, Amandine Deligey, Charlotte Journel, Justine Lamerre, and Michel-Pierre Faucon declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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