# Adjusting ley grassland duration in crop rotations to reconcile food production and soil carbon stocks

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## Abstract

Introduction of grasslands into cropping systems represents a strategy to ensure food production while reducing soil carbon losses. Yet, mixed crop and grassland management systems need to be evaluated in terms of achieving balanced food production and soil carbon (C) sustainability. The objectives of the study are: 1) to explore the impact of grassland duration on C input and soil C changes in agricultural systems; and 2) to test the variation in C input and soil C changes between rotations using grassland fertilized at high or low Nitrogen (N) application rates and their impacts on productivity. Field data regarding C input, soil C and crop production were collected during 2005–2016 from a longterm experimental site in Lusignan, France. Root biomass C was sampled annually, and the stable C isotope signature ($\delta^{13}C$) was determined to quantify the amount of C input from the root biomass. The results showed that integrating ley grassland in crop rotations increased the C input in the 0–30 and 0–60 cm soil layers ($P < 0.05$) but showed limited improvements in shoot biomass C and grain yield of these crops. In addition, C stocks also increased in the 0-30 cm but not always in the 0-60 cm layer. Compared with cropland, permanent grassland did not show a greater C input, whereas the latter showed a C stock increase of 0.6–1.4 Mg C $ha^{-1}$ $yr^{-1}$. In addition, in crop rotations integrated with ley grassland together with high-N or low-N fertilization did not impact C input, changes in soil C at either 0-30 cm or 0-60 cm soil layers, or even the crop production, while the grass production decreased by 22.2%-66.6% for low-N fertilization. In conclusion, integrating ley grassland in crop rotations increases the C input and soil C stocks in top soil, while reducing the time and production of crops.

**Key words**: Cropland; Grassland; Crop rotation; Carbon input; Soil carbon

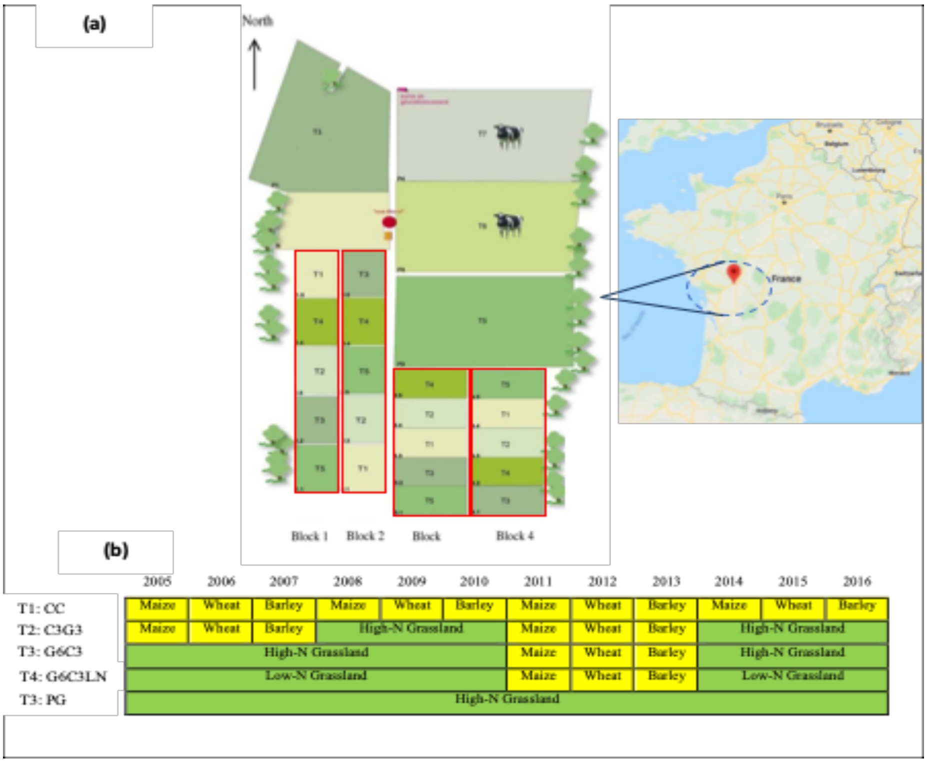
## Introduction

The depletion of soil C in agricultural systems has widely been reported (Hu et al., 2019), indicating its reduction in soil sustainability. A way to overcome this situation is to introduce grassland into cropping systems as a strategy to guarantee food production with the least amount of destruction of the soil for sustainable agriculture (Martin et al., 2020). While using perennial grassland reduces the time available for crops, it is necessary to evaluate mixed systems of crops and grasses to balance food production and sustainability. Moreover, research shows that applying fertilisers to grasslands may increase C stocks (Poeplau et al., 2018). Therefore, this idea is also related to the question of balance: can we reduce the application rate of N while similar productivity is maintained but with less negative impact on the environment?

To evaluate these properties of grasslands, field experiments involving crop rotations of different durations together with different fertilisation levels of ley grassland are necessary. Site experiments in Lusignan, France, based on conversions between cropland and N-fertilised grassland systems (Kunrath et al., 2015), provide an opportunity to evaluate the effects of the length of grassland in crop rotations, as well as the N application rates in grasslands. Maize, the only C4 plant species used in these rotations, helps quantify the C input from root biomass. Moreover, root biomass C is typically calculated using estimations (Berti et al., 2016), while the above- and belowground biomass at Lusignan was sampled every year, showing their contributions of C inputs with the lowest amount of estimation and assumption. These experiments also provide an opportunity to compare the recalcitrance between shoots and roots, although there are still inconsistent results (Sievers and Cook, 2018). Therefore, for sustainable crop production, the objectives of this study are 1) to investigate the impacts of grassland duration on C inputs and changes in soil C in agricultural systems and 2) to explore the variations in C inputs and changes in soil C between rotations using ley grassland fertilised at a high- or low-N application rate. We also examine the differences between above- and belowground C inputs in terms of their contributions to soil C stocks. In addition, this study measured C inputs and changes in soil C down to a 60 cm depth.

## Methods

The experimental site is part of a long-term observatory for environmental research located in Lusignan, Nouvelle-Aquitaine, France (46°25′12.91″ N, 0°07′29.35″ E). The experiment at the site started in 2005, and there were 4 randomised blocks. Treatments were replicated once in each block (Fig. 1); thus, each treatment had a total of 4 replicates. There were five treatments: Treatment 1 (CC) was the continuation of a 3-year cropland rotation with a sequence of maize (*Zea mays* L.), winter wheat (*Triticum* spp.) and winter barley (*Hordeum vulgare* L.); Treatment 2 (C3G3) was a rotation involving a 3-year cropland and a 3-year grassland receiving high-nitrogen (N) applications; Treatment 3 (G6C3) involved a rotation of a 6-year grassland receiving high-N applications followed by a 3-year cropland; Treatment 4 (G6C3LN) involved a rotation of a 6-year grassland receiving low-N applications followed by a 3-year cropland; and Treatment 5 (PG) was permanent grassland receiving high-N applications. A mixture of grasses, viz. *Dactylis glomerata* L., *Festuca arundinacea* Schreb. and *Lolium perenne* L., was used in all grasslands.



| | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1: CC | Maize | Wheat | Barley | Maize | Wheat | Barley | Maize | Wheat | Barley | Maize | Wheat | Barley |
| T2: C3G3 | Maize | Wheat | Barley | High-N Grassland | | | Maize | Wheat | Barley | High-N Grassland | | |
| T3: G6C3 | High-N Grassland | | | | | | Maize | Wheat | Barley | High-N Grassland | | |
| T4: G6C3LN | Low-N Grassland | | | | | | Maize | Wheat | Barley | Low-N Grassland | | |
| T3: PG | High-N Grassland | | | | | | | | | | | |

**Figure 1. Lusignan national long-term observatory experiment in the Nouvelle-Aquitaine region of France. Target plots in this study are marked in red frames (a); land-use management of target treatments (b).**

In the 3-year cropland, maize was sown in approximately mid-April, while winter crops were sown in approximately late October. Maize straw was maintained in the field after harvest. At the start of the grasslands, grasses were sown in approximately early May. The aboveground biomass of grasses was mowed and removed 3–4 times per year before each N application. When terminating the grasslands, a mouldboard plough was used, reaching soil to a 25–30 cm depth. Herbicide was applied to crops when necessary.

In 2005, 2008, 2011, 2014 and 2017, soil samples were collected in March in the 0-30 and 30-60 cm layers and always before land-use conversion. The soil total organic C (TOC) and total N (TN) contents were analysed with an elemental analyser (CHN NA 1500, Carlo Erba). The grain yields of crops were recorded for each plot at harvest, and the aboveground dry biomass of grasses was measured after each mowing. Crop residue, including straw, stubble and roots, was also sampled at harvest, and the roots in the grasslands were sampled in February. Aboveground samples were collected in a 1 $m^2$ square area. The roots were sampled from 0-30 and 30-60 cm soil layers with a stainless-steel cylinder (diameter of 6.7 cm). The $\delta^{13}C$ abundance of the crop roots was measured every October since 2005. Because of the possible disturbances from the previous roots, the historical $\delta^{13}C$ signatures of each plant at the Lusignan site during 2005-2016 were ranked, and the three least diluted values were averaged as their standard $\delta^{13}C$ signatures. The $\delta^{13}C$ standard signatures were -13.1‰ (SD=0.1‰) for maize, -28.5‰ (SD=0.2‰) for winter wheat, -29.5‰ (SD=0.6‰) for winter barley and -30.3‰ (SD=0.1‰) for all grasses. The ratio of the target root biomass C was determined for each sample of maize and winter wheat with the equation below:

$$P_t=(\delta^{13}C_s-\delta^{13}C_f)/(\delta^{13}C_t-\delta^{13}C_f)\ldots\ldots(1)$$

## Results and Discussion

Grasslands in conjunction with crop rotations have been reported to increase C stocks in topsoil by approximately 0.3 to 1.9 Mg C $ha^{-1}$ $yr^{-1}$ (Rosenzweig et al., 2016, Hu et al., 2018). In this study grassland treatments, in the 0-30 cm soil, incorporating grassland raised C stocks by 0.3-1.3 Mg C $ha^{-1}$ $yr^{-1}$ in 2013, while in 2016, they increased by 0.3-0.6 Mg C $ha^{-1}$ $yr^{-1}$. These rates were within the range of 0.3-1.9 Mg C $ha^{-1}$ $yr^{-1}$

reported by Hu et al. (2018). At 0-60 cm, in 2013, the range was 0.3-1.4 Mg C $ha^{-1}$ $yr^{-1}$, which changed little; while in 2016, the rates of increase ranged from 0.0 to 0.6 Mg C $ha^{-1}$ $yr^{-1}$, indicating C loss in the subsoil.

In 2013 and 2016, the permanent grassland had the greatest increase in soil C at both depths, even though the increases were not always significant. However, the C input from the permanent grassland was not significantly higher than the C input from crop rotations (CC) or even significantly higher than the belowground C input in the grassland treatments (C3G3, G6C3 and G6C3LN). Therefore, this large increase in C stocks in the permanent grassland cannot be explained by the amount or even quality of C input; rather, it indicated good preservation and thus a lower decomposition of soil C in the permanent grassland (Scott et al., 2021).

The C input in the permanent grassland originated from rhizodeposition supplied by the perennial root system. Therefore, there could have been a continuous interaction between the root systems and microbes (McGowan et al., 2019). In contrast, C input from annual cropping systems occurs from aboveground residue, rhizodeposition and dead roots, and annual root systems need to regrow every year. When the C supply is not sufficient for decomposers, decomposition of soil C becomes inevitable. Moreover, management practices such as applying mineral fertilisers and tillage may even hasten labile C decomposition (Qiu et al., 2016; Yu et al., 2017).

After converting the grassland to cropland, higher soil C increases in the 6-year grasslands (G6C3 and G6C3LN) than in the C3G3 treatment (3 years of cropland following 3 years of grassland) at 0-30 cm in 2011 were not observed in 2013. During the three-year duration, the soil C in C3G3 increased, while that in G6C3 and G6C3LN decreased; all of these contents were ultimately approximately 0.2 Mg C $ha^{-1}$ $yr^{-1}$. They were no longer significantly different in 2013 and 2016. The opposite trends of changes in soil C and their similar C inputs indicated more C loss in the six-year grasslands, probably because of the higher quantity of labile C stored during the grassland period (Yu et al., 2017).

Moreover, Conant et al. (2017) observed C sequestration of 0.5 Mg C $ha^{-1}$ $yr^{-1}$ in response to inorganic fertilisation in grasslands. Poeplau et al. (2018) reported that at seven locations in Europe, using only N did not significantly change the soil C or root C stocks at 0-30 cm. In this study, the gaps in the changes in soil C between high-N-fertilised grassland and low-N-fertilised grassland were not significant, nor were the C inputs from grassland at either 0-30 cm or 0-60 cm depths. Grasses in the low-N-fertilised grassland contributed 15% (0.3 Mg C $ha^{-1}$ $yr^{-1}$) of the C input at 30-60 cm, which was more than the amount contributed by the high-N-fertilised grassland, 10% (0.2 Mg C $ha^{-1}$ $yr^{-1}$). Thus, N application altered the distribution of grass roots but barely affected the belowground C input and soil C stocks in the grassland at the sampled depths.

It is generally expected that ley grasslands improves the sustainability of arable systems through various ecosystem services (Martin et al., 2020). However, the introduction of ley grasslands in crop rotations results in shared crop rotation time with grasses, which potentially reduces total crop production as shown in Figure 2. When compared with the cereal yield of continuous crops, the cereal yield of crops after grassland did not show an overall improvement in our study. The results could be attributed to the reduction in their N application, which provided opportunities to ensure food production with revised environmental risks from N application. Soils in both rotations involving 6-year-old grasslands fertilised at high- or low-N application rates were similar in terms of C input and soil C changes. Despite their similarities, low-N application could result

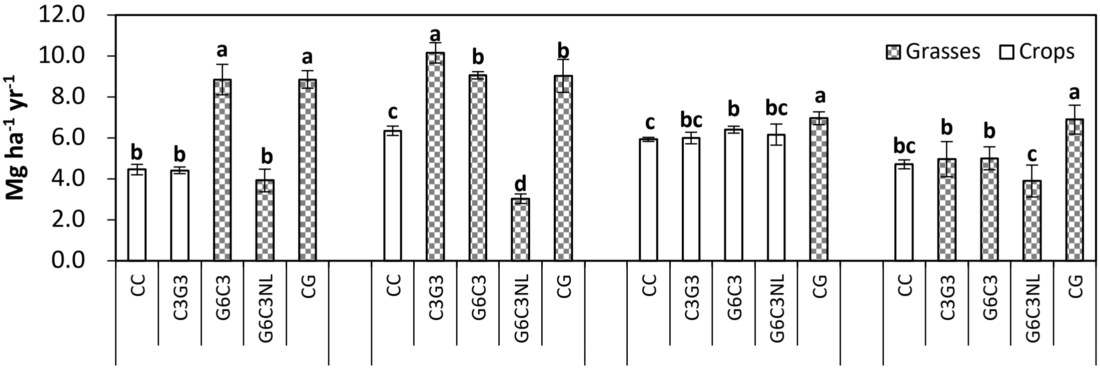


**Fig. 2. Yield of crop grains and above-ground grass production (Mg $ha^{-1}$ $yr^{-1}$) from different land-use conversion patterns during 2005-2007, 2008-2010, 20011-2013 and 2014-2016. The error bars are the standard deviations. During each period, the mean yields for crops and grasses with different letters are significantly different at the 0.05 significance level, based on one-way ANOVA (N=4).**

in a risk of reduced grass surface production (Fig. 2) and increased weed invasion (Schuster et al., 2020). In addition, compared with the 3-year (high N) grasslands, the 6-year (high N) grasslands and crop rotations did not result in either increased C inputs or increased soil C stocks. However, as noted already, more time spent on grasses reduced the time spent on crops and therefore crop production. It is therefore preferable to use grassland for 3 years and apply high-N fertilisers. Nevertheless, as indicated in our results, the use of grassland for 3 years fertilised at a low rate of N application is not suggested in crop rotations due to reduced crop and grass production. In addition, the use of grasslands in crop rotations did not reduce the belowground C supply from crops, indicating that in the third cropping season (2011-2013), the belowground C supply from cropland converted to grassland was 2-3 times greater than that from permanent cropland (Hu and Chabbi, 2021). Furthermore, numerous field studies have focused on the topsoil (Hu et al., 2018), presuming that the decreased soil C returned to the atmosphere. At the 30-60 cm soil layer in our observations, the soil C showed an obvious increase in 2013 and then decreased in 2016, suggesting that part of the C in topsoil might be stored deeper in the soil and that deep soil C might also decompose rapidly.

## Conclusions

Although the incorporation of grasslands into the crop rotation reduced crop production, it increased the C supply to the 0-30 and 0-60 cm soil layers. Crop rotations with grasslands also increased C stocks in the 0-30 cm soil layer but did not always increase C in the 0-60 cm soil layer. Compared with cropland, the permanent grassland did not receive more C input, whereas its soil C stock increased by 0.6-1.4 Mg C $ha^{-1}yr^{-1}$. This increase, however, did not occur in the crop rotation with the ley grasslands. The incorporation of 3-year grassland or 6-year grassland did not show significant differences in C input, changes in soil C or crop production afterwards. In addition, grasslands receiving high- and low-N applications did not differ in terms of their effects on C input or changes in soil C in the crop rotation but they differed in grass production. Moreover, in both the 0-30 and 0-60 cm soil layers, analysis of C input and soil C stocks suggested not using different contributions of above- and belowground C input; rather, the results suggested combining the two.

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