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Maximizing soil organic carbon stocks through optimal ploughing and renewal strategies in (Ley) grassland

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Grassland management effects on soil organic carbon storage under future climate are unknown. Here we examine the impact of ley grassland durations in crop rotations on soil organic carbon in temperate climate from 2005 to 2100, considering two IPCC scenarios, RCP4.5 and RCP8.5, with and without atmospheric CO_2 enhancements. We used the DailyDayCent model and a long-term experiment to show that ley grasslands increase soil organic carbon storage by approximately 10 Mg ha^{-1} over 96 years compared with continuous cropping. Surprisingly, extending ley duration from 3 to 6 years does not enhance soil organic carbon. Furthermore, in comparison with non-renewed grasslands, those renewed every three years demonstrated a notable increase in soil organic carbon storage, by 0.3 Mg ha^{-1} yr^{-1}. We concluded that management of ploughing and renewal intervals is crucial for maximizing soil organic carbon stocks, through balancing biomass carbon inputs during regrowth and carbon losses through soil respiration.

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Recent studies have shown that arable cropping soils have lost their soil organic carbon (SOC) stocks[1]. In regions with temperate climates, arable cropping practices have been linked to reductions in SOC contents ranging from 30 to 60%[2–5]. This depletion of SOC is typically attributed to soil disturbances like ploughing and the limited input of carbon (C) from plant biomass[6].

Incorporating ley grasslands into crop rotations has been proposed as a strategy to mitigate SOC depletion[7]. Transitioning from permanent grassland to annual crop rotations often results in SOC losses[8,9], while the introduction of ley grasslands seems to enhance the sustainability of arable cropping systems, likely due to their positive impact on SOC storage[10–12]. Short-term evidence suggests that even a single ley-cropping cycle can help maintain SOC stocks[13,14], possibly because grasses efficiently utilize nutrients and allocate a substantial biomass below-ground[15,16], which tends to be more recalcitrant and better stabilized than above-ground residues in the mineral soil[17,18]. Additionally, the absence of ploughing during the ley grassland phase minimizes soil disturbance. To effectively prevent SOC losses in agroecosystems, it is essential to accumulate SOC during the ley grassland phase to recover the C lost during crop rotations. Thus, the duration of the ley grassland phase plays a crucial role in enhancing SOC storage in these systems. However, due to limited long-term field experiments integrating grasslands with varying durations into crop rotations, coupled with the uncertainties of climate change effects, modelling approaches are instrumental in determining the optimal ley grassland duration.

In this study, the DailyDayCent model was employed to investigate how the addition of ley grassland of different durations into crop rotations impacts SOC stocks. This model considers key processes across the plant-soil-atmosphere continuum to estimate C inputs and losses[19,20]. In addition to ley grasslands with different durations, we modelled the SOC stock changes of continuous crop and grassland systems with contrasting renewal times in order to quantify the effect of ploughing and renewal of ley grasslands on SOC losses. The aims of this study were two fold: (1) to evaluate changes in SOC stocks in both cropping and grassland systems under current and future climatic conditions, and (2) to assess how the duration of ley grasslands influences SOC stocks in agricultural soils, particularly in the context of climate change. The findings of this study hold the promise to deepen our understanding of SOC dynamics within agroecosystems. In addition, they offer valuable insights into the effectiveness of adaptive management strategies in the face of changing climate conditions.

This investigation drew upon data from a long-term field experiment in Western France with continuous cropland, grassland and ley grasslands of contrasting durations (Fig. 1), where ploughing was applied to the top soil layer (25–30 cm). To understand the long-term implications of grassland duration, and their ploughing, and renewal under different grassland management strategies, we used two IPCC scenarios (RCP4.5 and RCP8.5), with and without atmospheric CO_2 enhancements, from the Institute Pierre Simon Laplace (IPSL) and the French National Centre for Meteorological Research (CNRM). We used multiple scenarios and data sources with and without atmospheric CO_2 elevation to understand the uncertainty in future conditions. We hypothesized that increasing the duration of grasslands would lead to increasing SOC stocks as a result of greater below-ground C input and reduced SOC loss through soil disturbance by less frequent ploughing events[8,9]. In this study, SOC does not include the C in undecomposed plant residues.

Results

DailyDayCent model validation. To understand how well the DailyDayCent model can capture the ecosystem dynamics of agricultural treatments, we compared observed and simulated NEE and SOC for a continuous grassland (PG) and for a crop rotation with a three year ley grassland phase (C3G3). While simulated daily NEE had an R-square of 0.46 for PG and 0.58 for C3G3, comparing total monthly NEE yielded an R-square of over 0.7 for both PG and C3G3. Moreover, the R-square for the simulated and observed SOC was 0.70, indicating that the model can capture the variability in C dynamics across treatments.

Climate scenarios. At the Lusignan National long-term observatory experiment, the RCP4.5 scenario showed a 0.5 °C to 0.9 °C lower average temperature than the RCP8.5 scenario. However, RCP4.5 and RCP8.5 scenarios did not exhibit clear trends in annual precipitation. When CO_2 enhancement was included in simulations, the CO_2 background in the RCP8.5 scenarios increased faster than in RCP4.5 scenarios. Under all 8 climate scenarios (2 RCP scenarios × 2 CO_2 conditions × 2 data sources) from 2005 to 2100, simulations showed strong consistency in the trends between treatments, thus the average model results under the 8 climate change simulations were calculated for each treatment. The variations reported below were the standard deviations resulting from the 8 future climate simulations for the following treatments including six continuous grasslands: G1 (grassland ploughed and restarted every year), G2 (grassland ploughed and restarted every two years), G3 (grassland ploughed and restarted every three years), G4 (grassland ploughed and restarted every four years), G6 (grassland ploughed and restarted every six years) and PG (grassland with no tillage); and three crop rotations: CC (rotation of annual crops), C3G3 (rotation of 3-year grasses and 3-year annual crops), G6C3 (rotation of 6-year grasses and 3-year annual crops).

Biomass C input. The biomass C input from continuous grasslands between 2005 and 2100 ranged from 403.5 to 568.8 Mg C ha^{-1}. Biomass C inputs were greatest when continuous grasslands were ploughed and restarted every three years (568.8 ± 35.8 Mg C ha^{-1}) (Fig. 2). The biomass C input from crop rotations without ley grassland phases was on average 299.6 ± 14.7 Mg C ha^{-1}. As biomass C input increased with the introduction of ley grasslands, longer ley grassland phase duration might provide greater benefits. For example, the inclusion of a 3-year ley grassland phase showed a biomass C input of 437.7 ± 22.8 Mg C ha^{-1} and crop rotations with a 6-year ley grassland had a a biomass C input of 481.4 ± 25.6 Mg C ha^{-1}.

Heterotrophic respiration (Rh). On average, Rh from continuous grasslands ranged between 428.0 and 570.7 Mg C ha^{-1} (Fig. 2). The Rh was greatest when the grassland was ploughed and restarted every three years, rather than from the grasslands that were ploughed and renewed at other frequencies (Fig. 2). For crop rotations without ley grassland phases, Rh was 336.2 ± 13.1 Mg C ha^{-1}. Respiration increased with the introduction of ley grasslands and with longer durations. The inclusion of a 3-year ley grassland resulted in an Rh of 455.6 ± 20.3 Mg C ha^{-1} and the inclusion of a 6-year ley grassland showed the highest Rh (495.4 ± 23.4 Mg C ha^{-1}).

Carbon balance of the agroecosystems. In Fig. 3, when considering the net ecosystem C balance (NECB), all treatments exhibited a loss of C from the system, even before accounting for CO_2 enhancement. But some treatments, like continuous grasslands ploughed and restarted every two to four years

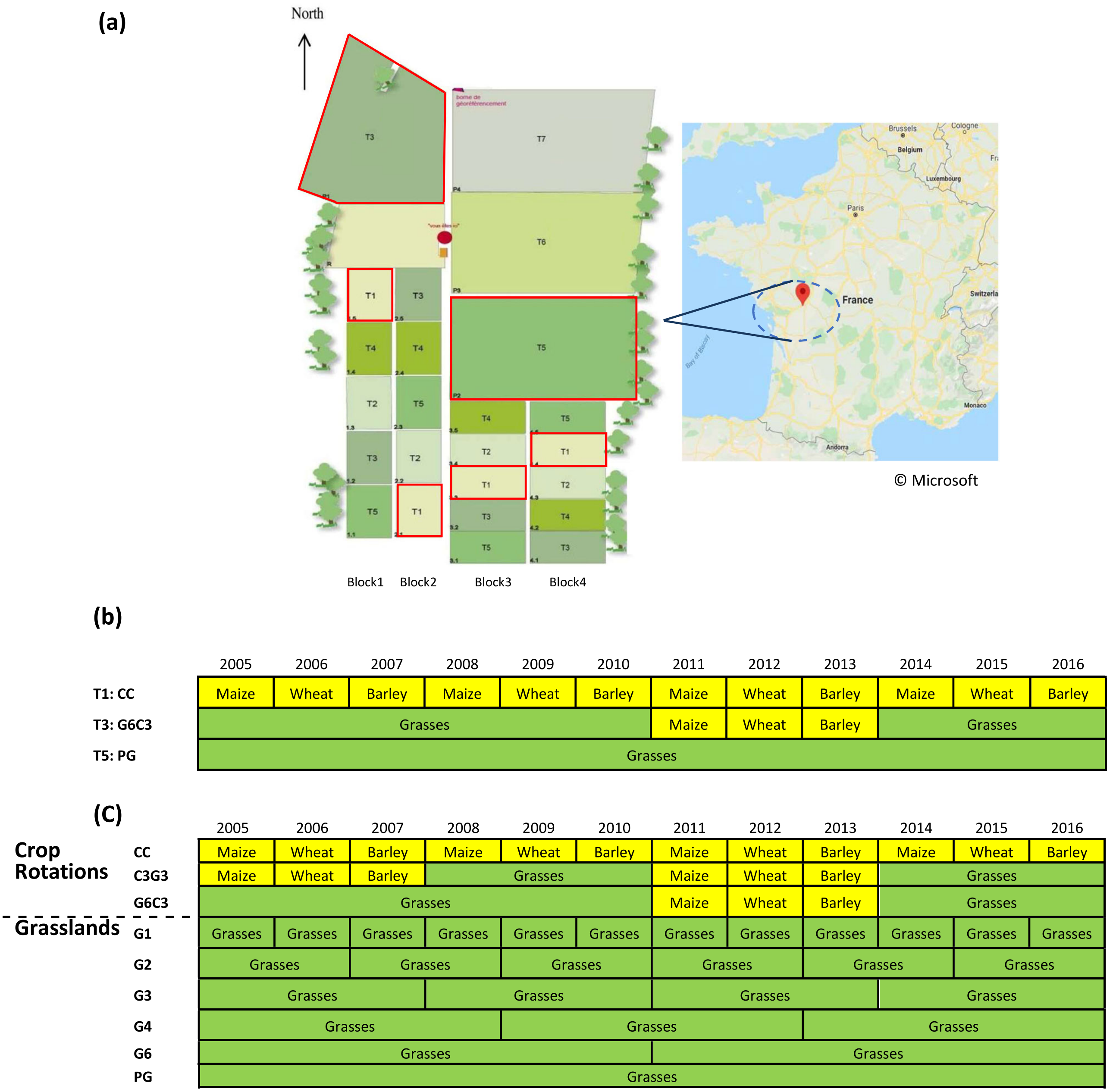

Fig. 1 **Experience of the national long-term observatory at Lusignan in the Nouvelle-Aquitaine region of France. a** Target plots in this study are marked in red frames. **b** Land use management of target treatments. **c** Simulated treatments in DailyDayCent model under future climate change scenarios from 2005 to 2100, including six continuous grasslands: G1 (grassland ploughed and restarted every year), G2 (grassland ploughed and restarted every two years), G3 (grassland ploughed and restarted every three years), G4 (grassland ploughed and restarted every four years), G6 (grassland ploughed and restarted every six years) and PG (grassland with no tillage); and three crop rotations: CC (rotation of annual crops), C3G3 (rotation of 3-year grasses and 3-year annual crops), G6C3 (rotation of 6-year grasses and 3-year annual crops).

(G2, G3 and G4), gained C when the CO_2 fertilization effect was taken into account. Our data showed that C loss from cropping systems could be lessened by 18.7 ± 4.9 Mg C ha^{-1} and 22.6 ± 4.9 Mg C ha^{-1} with the inclusion of a 3-year or a 6-year ley grassland phase.

Moreover, SOC stocks generally decreased in all treatments (Figs. 3 and 4). For continuous grasslands, G3 exhibited higher SOC stocks than grasslands of other ploughing and renewal frequencies, losing on average 8.5 ± 4.9 Mg C ha^{-1}. For crop rotations, C3G3 and G6C3, SOC declined by 21.7 ± 4.2 Mg C ha^{-1} and 22.6 ± 3.7 Mg C ha^{-1} respectively, from 2005 to 2100. These two treatments maintained ~10 Mg C ha^{-1} more SOC than continuous cropland (CC) under all scenarios.

Undecomposed plant residue C was categorized as C in the residue pool, rather than in the SOC pool. For continuous grasslands, when we lowered the renewal frequency, there was more C in the residue pool. Similarly, increased C in the residue pool was also observed in crop rotations with increasing ley grassland duration (Fig. 3).

Discussion

Numerous studies highlight the critical role of C input from plant biomass in enhancing the storage of SOC[21]. Conversely, other research emphasizes the impact of soil disturbance, particularly through ploughing, as a significant factor driving SOC losses[8–11].

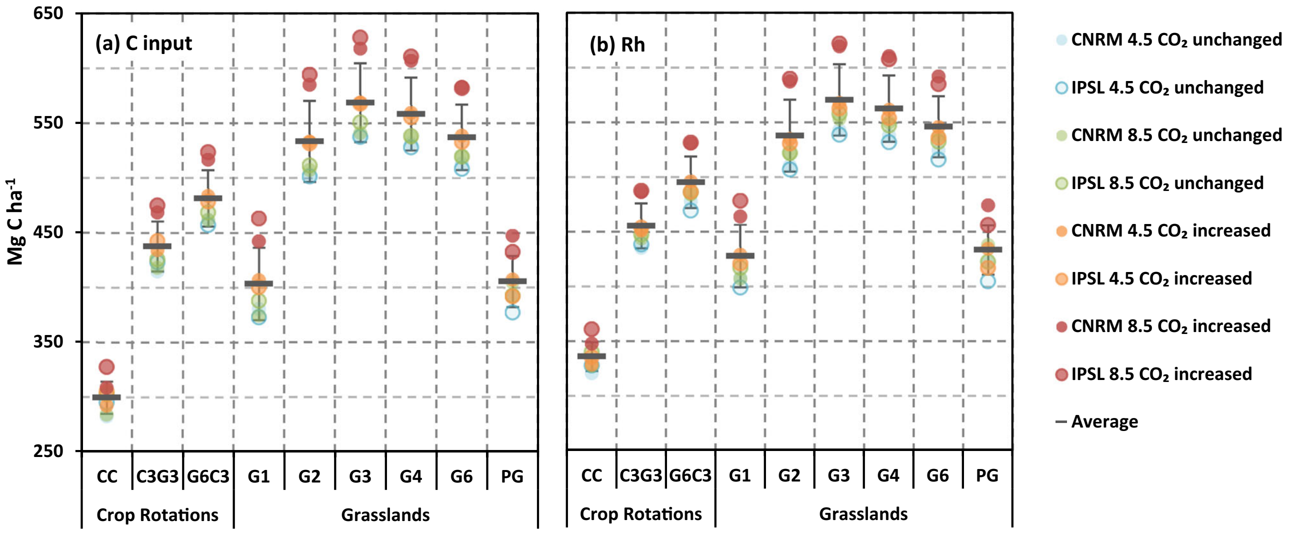

Fig. 2 Carbon input and heterotrophic respiration for continuous grasslands and crop rotations. a Simulated accumulated soil carbon input (C input) and **b** accumulated soil respiration (Rh) from 2005–2100 under climate change scenarios (IPCC scenarios RCP: 4.5 with and without 538 ppm CO$_2$ enhancement and 8.5 with and without 935 ppm CO$_2$ enhancement; data sources: CNRM and IPSL). Treatments included six continuous grasslands: G1 (grassland ploughed and restarted every year), G2 (grassland ploughed and restarted every two years), G3 (grassland ploughed and restarted every three years), G4 (grassland ploughed and restarted every four years), G6 (grassland ploughed and restarted every six years) and PG (grassland with no tillage); and three crop rotations: CC (rotation of annual crops), C3G3 (rotation of 3-year grasses and 3-year annual crops), G6C3 (rotation of 6-year grasses and 3-year annual crops). Graphs show the mean and standard deviation across the 8 scenarios.

The disruption caused by ploughing can accelerate the decomposition of organic matter by exposing it to increased microbial activity and aeration. As a result, the soil's C sequestration capacity is compromised, leading to a reduction in SOC levels. This dual perspective underscores the complexity of SOC dynamics, highlighting the need for a comprehensive understanding of both C input mechanisms and potential sources of disturbance to formulate effective soil management strategies. Therefore, introducing ploughed and renewed ley grassland at an optimal duration presents an opportunity to enhance SOC. The magnitude of SOC stocks within an ecosystem is influenced by factors such as biomass input, decomposition rates, soil texture, and climate[8]. These factors interact and collectively influence changes in SOC over time. While we hypothesized that SOC stocks would be enhanced by increasing the duration of ley grassland phases, our results showed that the NECB and SOC stocks were generally dependent on ley grassland duration with the highest values observed for ley grasslands renewed every three years. This suggests that adjusting the frequency of renewal can optimize ley grassland phases to enhance SOC.

Contrary to the negative impact of ploughing on annual cropping systems, where annual ploughing can accelerate SOC decomposition[20,22,23], recent research on the use of full inversion tillage for pasture/grassland renewal suggests that a one-off (or very infrequent) ploughing may actually lead to enhanced SOC sequestration over time[24–26]. This is attributed to reduced decomposition of buried SOC after inversion tillage and the accumulation of SOC in exposed subsoils due to ploughing[24–26]. Although a period of low SOC sequestration occurs after existing grasslands are ploughed before resowing, it is rarely emphasized that ploughing directly incorporates much of the plant residues and living biomass into the soil, acting as a substantial C input[22]. This process may be important, especially for converted perennial systems. Moreover, the C input from root biomass occurs in all annual systems, whereas in perennial systems with a living root system, this C input may not occur without ploughing[24–26]. Therefore, if the C incorporated into the soil by ploughing during grassland conversion is larger than the C lost by decomposition following the disturbance, it will enhance the SOC stocks. Our results for grasslands showed that Rh increased from permanent grassland to G3, but dropped again with shorter grassland duration. Even if there was more C loss through Rh in G3, this did not exceed the benefit of ploughing-induced C input. In addition, the C input from below-ground parts of the vegetation in our study did not further increase when the duration of ley grassland phases was greater than three years. The higher C input in G3 indicates that roots grow rapidly in early years of grassland renewal[14]. In addition, the lower C input in the continuous grassland system suggests that managing the duration of grasslands by ploughing provides extra biomass C input and the potential for more C sequestration. It is clear that ploughing accelerated the decomposition of C in the residue pool[27], which was much lower than the SOC stock. Hereby, in terms of our results, G3 grassland is preferred for its SOC sequestration capacity over other durations, and ploughing and renewal of every 3 years is thus the optimal grassland management at our site under current and future climate scenarios.

Similar to our previous experimental results, treatments with 3-year or 6-year ley grasslands within crop rotations showed small differences in their SOC stock changes of soil C stock[13,14], which could be ascribed to the large quantity of labile C stored during the grassland period [28,29]. However, the large improvements of C in residue pools in the G6C3 over C3G3 indicate that the crop rotation with a 6-year ley grassland tends to preserve more undecomposed residues in the agroecosystem[27]. This might be explained by the reduced soil disturbances due to a longer grassland period. Over longer time periods, the proportion of time between crop and ley grassland phases in rotations is an important management factor to consider, as it not only influences the quantity of soil C input but also the decomposition of residues in soil. Moreover, compared with continuous crops, crop rotations with ley grasslands reduced SOC losses by around 10 Mg C ha^{-1} (~0.1 Mg C ha^{-1} yr^{-1}), which was close to previous reports[13,14]. The results indicated that integrating ley grassland into crop rotation preserves SOC stocks, which is in line with other studies[10,13,30]. However, optimization of ley grassland phases is necessary to maximize this

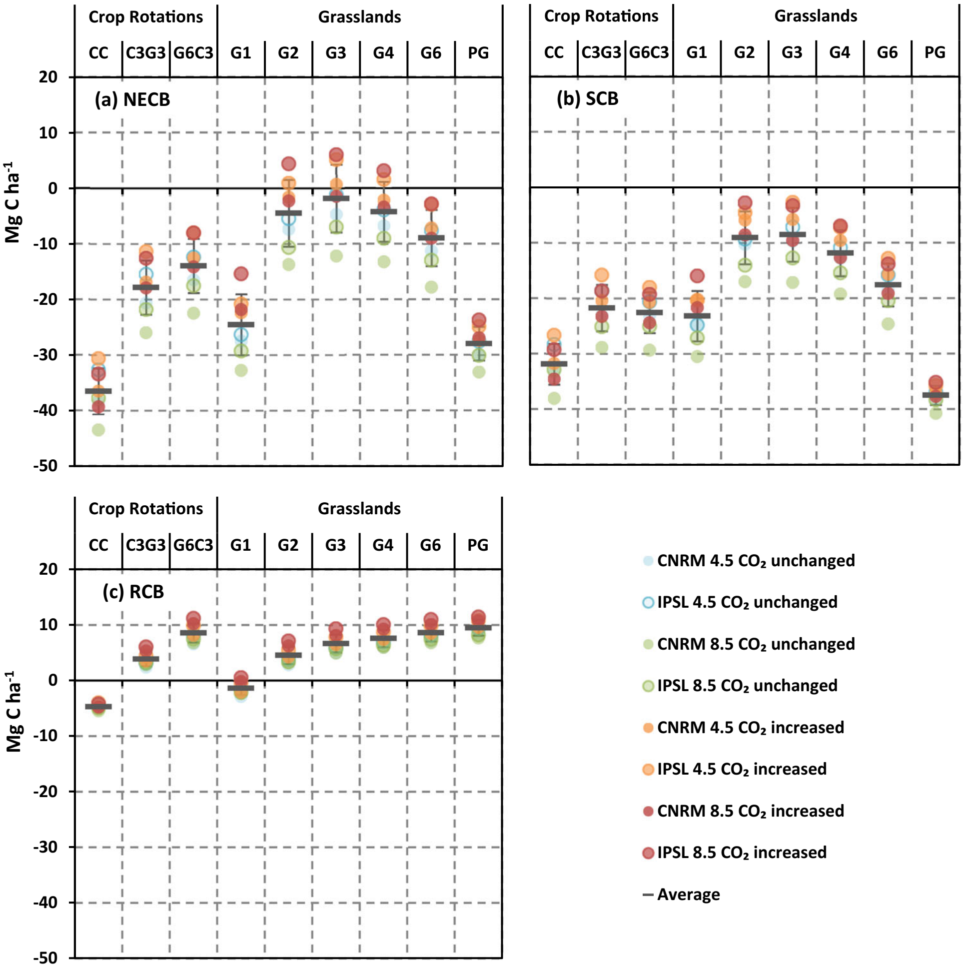

Fig. 3 The carbon balance of ecosystems, residues and soils for continuous grasslands and crop rotations from 2005 to 2100. **a** Simulated net C balance of the ecosystem (NECB), **b** C balance of residue pool (RCB) and **c** the balance of soil C (SCB) under different climate change scenarios (IPCC scenarios RCP: 4.5 with and without 538 ppm CO_2 enhancement and 8.5 with and without 935 ppm CO_2 enhancement; data sources: CNRM and IPSL). Treatments included six continuous grasslands: G1 (grassland ploughed and restarted every year), G2 (grassland ploughed and restarted every two years), G3 (grassland ploughed and restarted every three years), G4 (grassland ploughed and restarted every four years), G6 (grassland ploughed and restarted every six years) and PG (grassland with no tillage); and three crop rotations: CC (rotation of annual crops), C3G3 (rotation of 3-year grasses and 3-year annual crops), G6C3 (rotation of 6-year grasses and 3-year annual crops). Graphs show the mean and standard deviation across the 8 scenarios.

benefit. In addition, our results showed that continuous crop rotations lost C from the original residue pool, which could be prevented by introducing ley grasslands due to improved total C inputs from grasses and/or the reduced tillage. The improved C inputs and/or the reduced tillage could also be the reason why permanent grassland showed more C in the ecosytem and less SOC storage than continuous crop rotations, preserving more C in permanent grassland in the residue pool.

In Lusignan, France, RCP8.5 scenarios exhibited higher temperature over RCP4.5 scenarios (Supplementary Fig. 1). Higher temperatures contributed more to heterotrophic respiration than to biomass C inputs, even though the enhanced CO_2 could narrow the gap[31]. Therefore according to our results, SOC dropped less under RCP4.8 than that under RCP8.5 scenarios, with or without considering the atmospheric CO_2 enrichment. However, the temperature change showed limited impacts on the residue pools, thus the accelerated C loss in ecosystems under RCP8.5 showed SOC loss in the soil. The CO_2 enhancement pushed up the total biomass C inputs. Therefore, the C in residues and SOC also increased, as well as the heterotrophic respiration.

Overall, our results showed the potential of ploughing and ley grassland renewal in perennial systems to foster SOC sequestration under current and future climate scenarios, indicating the possibility of enhanced SOC sequestration through balancing C input and heterotrophic respiration (Fig. 5). For continuous grasslands, optimized intervals of grassland renewal can lead to large biomass C inputs from both living biomass and dead residues of matured grasses. These C inputs can be close to or even exceed the C loss from heterotrophic respiration. On the contrary, frequently ploughing and renewing ley grassland phases in a crop rotation can produce C inputs from young grasses which are not well-developed, while very low frequency ploughing and renewal can produce C inputs from mainly the dead residues[27]. Under too high or too low frequencies for plouging and renewal, biomass C inputs are too low relative to C loss through heterotrophic respiration[27]. Therefore, optimizing the ley grassland duration can support greater SOC storage, even though low renewal frequencies keep more C in residues which are not decomposed. For crop rotations, SOC loss through heterotrophic respiration is much greater than C inputs from continuous crops. The introduction of perennial leys into cropping systems can reduce the gap between C input from plant biomass and heterotrophic respiration, and thus increase SOC storage and C in residues. While prolonging the duration of leys had little effect on

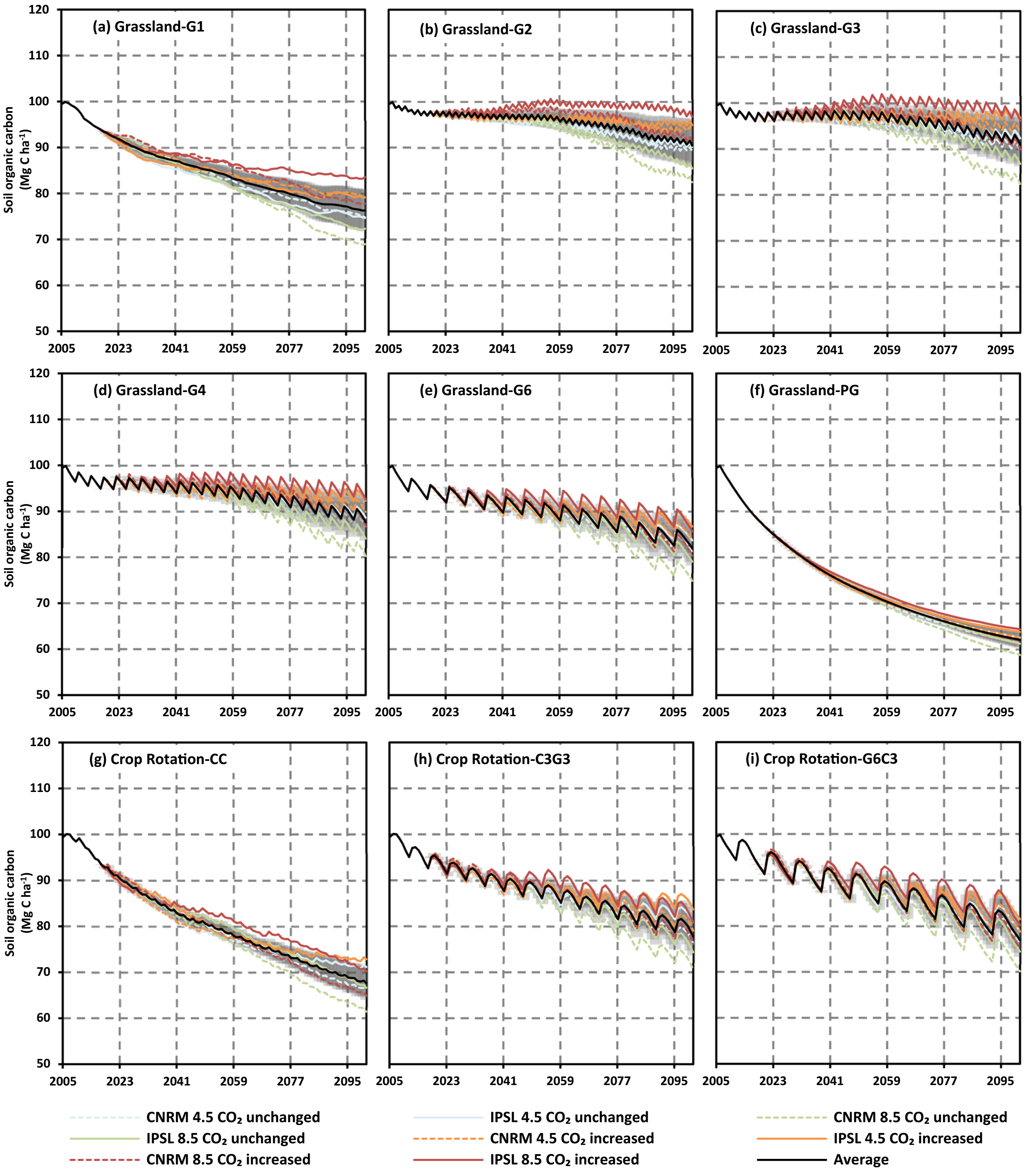

Fig. 4 Simulated soil organic carbon (SOC) stocks from 2005 to 2100. Climate change scenarios encompased IPCC scenarios RCP: 4.5 (with and without 538 ppm CO_2 enhancement) and 8.5 (with and without 935 ppm CO_2 enhancement) from climate data sources CNRM and IPSL. **a–f** Treatments included six continuous grasslands: G1 (grassland ploughed and restarted every year), G2 (grassland ploughed and restarted every two years), G3 (grassland ploughed and restarted every three years), G4 (grassland ploughed and restarted every four years), G6 (grassland ploughed and restarted every six years) and PG (grassland with no tillage); and **g–i** three crop rotations: CC (rotation of annual crops), C3G3 (rotation of 3-year grasses and 3-year annual crops), G6C3 (rotation of 6-year grasses and 3-year annual crops). Graphs show the mean and standard deviation across the 8 scenarios.

the SOC storage, it did result in an accumulation of undecomposed C in plant residues.

Soil and climate conditions are important determinantes of the optimal length of ley grassland duration. An evaluation of grassland ploughing and reseeding every 5 to 10 years on a sandy loam soils in Northern Germany suggested that SOC stocks will decline due to reduced gross primary production and increased soil respiration[27]. The amount of residue plant material at the time of ploughing and increased decay of native soil organic matter were identified as the main drivers for enhanced soil

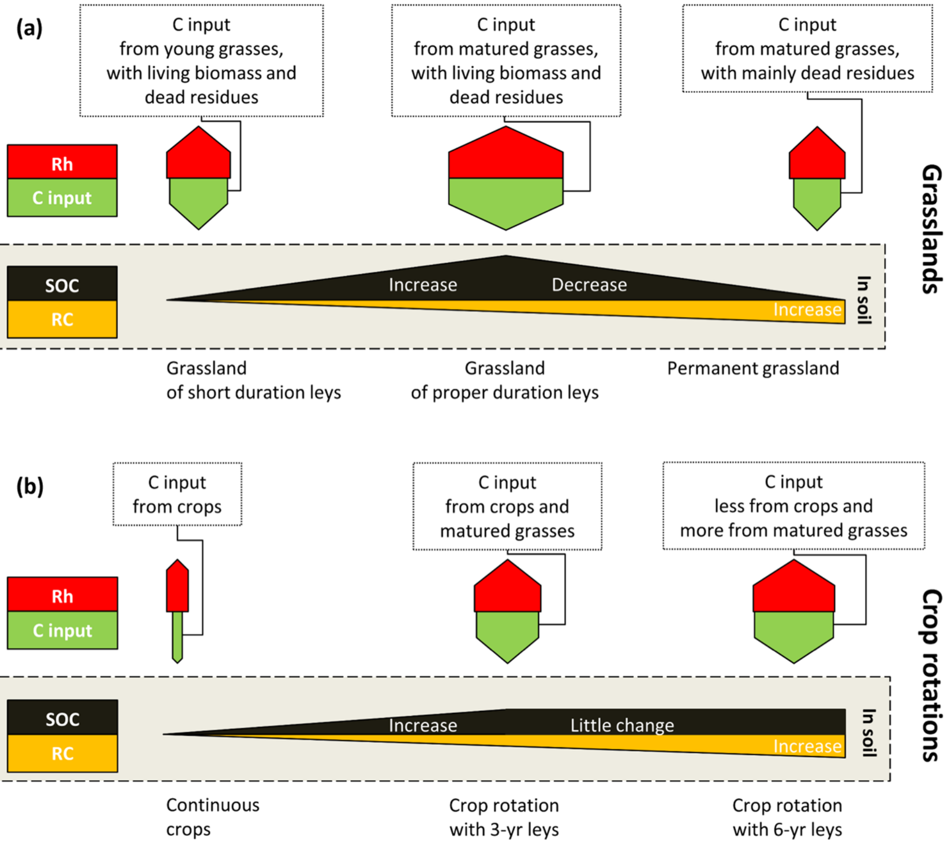

Fig. 5 Concept map of optimizing ley durations for continuous grasslands and crop rotations. Carbon (C) maintained in the ecosystem is the balance between C input from plants and C output through heterotrophic respiration (Rh), which is mainly exhibited through the soil organic carbon (SOC) storage and partly through C in undecomposed residues (RC). **a** For continuous grasslands, adjusting the ploughing and renewal cycles of leys can maximize the benefit of SOC storage by balancing C input and Rh. **b** For crop rotations, adjusting the duration of leys can maximize the SOC storage without requiring long ley durations.

respiration in the short term. Long-term (100 year) simulations indicated that net SOC stocks decreased by 21 and 14 Mg C ha^{-1}, compared with intact grasslands. Reinsch et al.[27] showed the consequences of insufficient C inputs considering decomposition rates and climate. With the use of simulation models, adaptive strategies for soil organic matter management can be developed to determine the conditions required for SOC management given soil type, climate, and crop types.

Even though there was only one model used in our study, and climate change can have strong effects on agricultural systems through climate-induced shifts in production and feedback on soil biochemistry[32], the projections from various climate conditions showed strong consistency that C losses could be mitigated by optimizing the durations of ley grassland phases. It is important to note that this study was concerned with a mowed grassland in western France. The optimal grassland duration in integrated crop-grassland systems most probably depends on region-specific pedoclimatic conditions and other management factors, which influence both biomass C input and heterotrophic respiration. Therefore, studies at other locations are necessary for adapting to variations in climate and soil conditions[33].

Methods

Experimental site. The experimental site, which started in 2005, is located at the Lusignan National long-term Observatory (46°25'12,91" N; 0°07'29,35" E), Poitou-Charentes, France (Agroecosystems, Biogeochemical Cycles and Biodiversity, SOEREeACBB; www.soere-acbb.com). The ACBB platform is dedicated to the long-term study of the role of agroecosystems and their management on biogeochemical cycles, environmental fluxes and biodiversity. The well-equipped platform records the temporal evolutions of soil-vegetation systems and the resulting agronomic performance and environmental impacts. The soil at the site can be divided into two main domains: upper soil horizons are characterized by a loamy texture, classified as a Cambisol, whereas lower soil horizons are clayey rubefied horizons, rich in kaolinite and iron oxides, classified as a Paleo-Ferralsol[34]. The region has a continental climate with average precipitation of ~800 mm annually and temperature averaging 12 °C. Summers are hot and dry while winters are cold and moist[35].

Experimental design of the ley grassland experiment. The analyzed treatments (Fig. 1) included continuous cropland (CC) with Maize (*Zea mays* L.), winter wheat (*Triticum* spp.) and winter barley (*Hordeum vulgare* L.) rotation, permanent grassland (PG) with a mixture of three species, viz. Lolium perenne L., Festuca arundinacea Schreb. and Dactylis glomerata L., and six-year grassland followed by a 3-year cropland (G6C3). In the 3-year cropland, the straws of maize were not removed from the field after harvest. In the grassland phases, above-ground biomass was mowed and removed 3–4 times each year. The N application rates are shown in Supplementary Table 1. The eddy covariance flux data were mainly performed for the treatment PG and G6C3.

Soil sampling and local weather monitoring. In 2005, 2008, 2011 and 2014, the soil was sampled in March at 0–90 cm depth, and always before the land use conversion. The SOC concentrations were analyzed using an elemental analyzer (CHN NA 1500, Carlo Erba). No carbonate was detected in the soil, thus the soil C was all SOC. Bulk densities of each 30 cm soil layer (0–30 cm, 30–60 cm and 60–90 cm) was measured in 2005 at the start of the experiment. The bulk density of the 0–30 cm soil was also determined in 2008, 2011 and 2014, showing no significant change. The soil bulk densities of 30–60 cm and 60–90 cm were assumed to be stable during the experiment. Meteorological data were collected at the experimental site on a 2.0 m tower (Fig. 1; Supplementary Fig. 1a). Data were stored on a CR3000 datalogger (Campbell Scientific, Logan, UT) and transferred back to the research center via ethernet. Meteorological data measured on the towers included: photosynthetically active radiation (PAR, LI-190SB, LI-COR Inc., Lincoln, NE), four component net radiation (Rn, CNR1, Kipp & Zonen, Delft), The Netherlands), precipitation (SBS500, Campbell Scientific, Logan, UT), air temperature (Tair) and relative humidity (HMP45C, Campbell Scientific, Logan, UT), and barometric pressure (CS100, Campbell Scientific, Logan, UT).

Soil temperature (T_{soil}) was measured at 10, 20, 30, 60 cm below the surface (CS107, Campbell Scientific, Logan, UT) and volumetric water content (VWC) of the soil was measured using water reflectrometer probes at 10, 20 30 and 60 cm below the surface (CS 616, Campbell Scientific, Logan, UT). T_{soil} and VWC were measured in one location in each of the treatment fields every 15 s and averaged every 30 min on an independently powered CR1000X datalogger.

Eddy covariance data collection. Net ecosystem exchange (NEE) was measured continuously at the two sites (Lusignan ICOS site) using open-path eddy covariance techniques[36]. Carbon dioxide (CO_2) and water vapour (H_2O) were measured with an open path infrared gas analyzer (IRGA, LI-7500, LI-COR Inc., Lincoln, NE) paired with a 3-D sonic anemometer at 20 Hz (R3-50; Gill Instruments, Lymington, UK) to measure three-dimensional wind speed and sonic temperature. These sensors were installed ~1.65 m above the soil surface at each site. The sonic anemometer and the IRGA were placed ~0.2 m apart to minimize flow distortion between the two instruments. The optical path of the IRGA was vertically aligned to match the sampling volume of the sonic anemometer. Data were logged on CR-3000 data loggers (Campbell Scientific, Logan, UT) and transferred back to the agricultural station at Lusignan via ethernet cable. Raw 20 Hz flux data were then processed using CarboEurope-IP guidelines to produce average 30-minute flux values (μmol $m^{-2}s^{-1}$)[37].

Flux data were filtered to eliminate 30-min fluxes resulting from systematic errors such as: (1) rain and condensation in the sampling path, (2) incomplete 30-min datasets during system calibration or maintenance, (3) poor coupling of the canopy with the external atmospheric conditions, as defined by the friction velocity, u*, using a threshold smaller than 0.10 m s^{-1} and (4) excessive variation from the half-hourly mean CO_2, LE or H statistics[38]. Quality assurance of the flux data was also maintained by examining plausibility ($-50 < NEE < 50$ μmol $m^{-2}s^{-1}$), stationarity criteria and integral turbulent statistics[39,40]. Missing half-hourly data were then gap-filled based on methods developed in Reichstein et al.[41].

Model set-up, parameterization and simulation. The DailyDayCent model was parameterized for the Lusignan sites experimental plots G6C3 and PG (Supplementary Tables 2 and 3). Site-specific parameters i.e. soil texture, filed capacity, wilting point, hydraulic conductivity, SOC, pH etc., were used for model parameterization[42,43], measured or estimated in 2005, as in Senapati et al.[35] and Senapati et al.[44]. Crop rotations (corn, wheat, barley, and meadow), fertilization, cultivation and harvesting were included in the model parameterization. Three time blocks were used to simulate the historical land-uses, (1) temperate-deciduous forest (6 CE to plough out-1750), (2) grass grazing (1750–1845), and (3) ley-arable rotation (1845–2004). Climate data on daily base from 2006–2015 was cycled and used for the model since 6 CE. Daily climate data (maximum and minimum temperature and daily total precipitation) recorded between 2006 and 2015 were used as drivers for the DAYCENT model spin-up (2000 years) and simulations. In DailyDayCent model, ploughing events transferred the above- and below-ground biomass to the top soil layer, and effect the decomposition rates of soil structural litter and soil organic matter in active, slow and passive pools.

Eddy covariance tower data from 2011 to 2014 were used in the initial parameterization and the parameter estimation software (PEST) was used to run the model 100,000 to focus on the parameterization of site and crop level parameters. The PEST software was used to improve the parameterization process, where NEE data and C in yield (grain yield for crops/harvested above-ground biomass C for grasses) were used simultaneously to reduce the bias. Root mean square error (RMSE) and model efficiency (MF) were used to show the model performance (In our study, model agreement was considered satisfactory when $0.40 \leq MF \leq 0.70$, and efficient when $MF > 0.7$ in terms of Senapati et al.[44]). Parameterization was run first for PG to calibrate the parameters in crop.100, fix.100 and sit.100. And these calibrated parameters were used to determine the maize, winter wheat and winter barley parameters in crop.100 for G6C3. Simulated C input of CC were compared with measured C input of CC from four blocks ($P < 0.05$). Simulations for the soil carbon balance (SCB) were checked with R-square ($P < 0.05$) considering the variations. Model performance is shown in Supplementary Fig. 2.

Following parameterization, local climate scenarios from Institute Pierre Simon Laplace (IPSL), and National Centre for Meteorological Research (CNRM) in France were used to simulate C dynamics into the future. Climate projection RCP4.5 and RCP8.5 for the study site during 2016–2100 were selected to represent future temperature and precipitation (Supplementary Fig. 1b, c). Concentrations of CO_2 were adjusted linearly by the DailyDayCent model from 2016–2100, where the concentration increased from default 350 ppm to 538 ppm for RCP4.5 and to 935 ppm for RCP8.5[31]. We ran the model for six continuous grasslands composed of different short-term grasslands (G1—grassland ploughed and restarted every year, G2—grassland ploughed and restarted every two years, G3—grassland ploughed and restarted every three years, G4—grassland ploughed and restarted every four years, G6—grassland ploughed and restarted every six years, and PG—permanent grassland with no tillage) and three crop rotations (CC—continuous cropland, C3G3—rotation of 3-year cropland followed by 3-year grassland, and G6C3—rotation of 6-year cropland followed by 3-year grassland).

Calculations of carbon balance. Net ecosystem carbon balance (NECB) was calculated based on Smith et al.[45]:

$$\mathrm{NECB} = \mathrm{NEE} + C_{Exo} - C_{Harvest} - C_{D} - C_{Fire} - C_{Volatile} - C_{CH4} - C_{Erosion} \tag{1}$$

Where C_{Exo} is the C from exogenous sources, i.e. organic manure and fertilizer; $C_{Harvest}$ is the C export when harvesting (grain and straw for crops/harvested above-ground biomass C for grasses); C_{D} is the C dissolved in water and leached from the system; $C_{Volatile}$ and C_{CH4} are C loss to the atmosphere. The C balance in a C pool in this study means the quantity of C storage it gains (positive value) or loses (negative value) during 2005–2100. Therefore, the positive NECB indicates the net C accumulation in the ecosystem, while the negative value indicates the net C loss.

Carbon losses associated with C_{EXO}, C_D, C_{Fire}, $C_{Volatile}$, C_{CH4} and $C_{Erosion}$ were low to negligible. Therefore we did not include them in the calculation of NECB, shortening Eq.1 to:

$$NECB = NEE - C_{Harvest} \quad (2)$$

Considering the following equation for NEE:

$$NEE = NPP - Rh \quad (3)$$

Where NPP is the net primary production and Rh is the heterotrophic respiration.

When replacing NEE in Eq. 2 with the Eq. 3, then

$$NECB = NPP - Rh - C_{Harvest} \quad (4)$$

Because there were no exogenous sources in our study, thus the C input to soil means the C in plant biomass which was not harvested, and was calculated as follows:

$$C_{Input} = NPP - C_{Harvest} \quad (5)$$

Therefore, NECB can also be calculated in the equation below:

$$NECB = C_{Input} - Rh \quad (6)$$

Moreover, assuming C storage in the ecosystem reaching 90 cm depth is composed of C in soil and C in residues, the C change in residue pool can then be calculated:

$$RCB = NECB - SCB \quad (7)$$

Where RCB means residue C balance, and SCB indicates soil C balance.

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available via the link: https://doi.org/10.57745/EDE2KA.

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Author contributions

T.H.: Validation, Visualization, Methodology, Writing original draft, Writing—review & editing. S.M.: Data curation, Validation, Visualization, Writing original draft,—review & editing. C.R.: Review & editing. A.C.: Conceptualization, Formal analysis, Writing original draft, Writing—review & editing, Funding acquisition, Investigation, Project administration, Resources, Supervision.

Inclusion and ethics statement

We support inclusive, diverse, and equitable conduct of research

Competing interests

The authors declare no competing interests.

Additional information

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