



# Integrated crop and livestock systems increase both climate change adaptation and mitigation capacities

Mathieu Delandmeter<sup>a,\*</sup>, Paulo César de Faccio Carvalho<sup>b</sup>, Carolina Bremm<sup>b</sup>,  
Carolina dos Santos Cargnelutti<sup>b</sup>, Jérôme Bindelle<sup>c</sup>, Benjamin Dumont<sup>a</sup>

<sup>a</sup> Liege University, Gembloux Agro-Bio Tech, TERRA Teaching and Research Centre, Plant Sciences/Crop Science, Passage des Déportés 2, 5030 Gembloux, Belgium

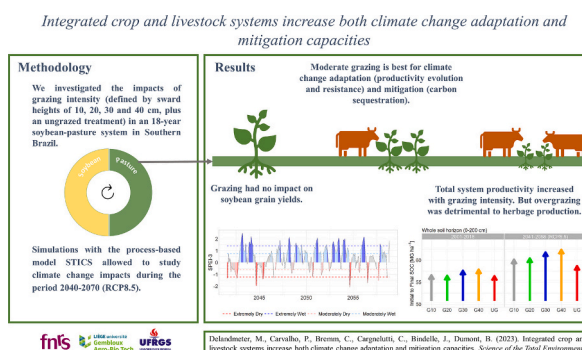
<sup>b</sup> Federal University of Rio Grande do Sul, Animal Science Research Program, Bento Gonçalves Avenue 7712, 91540-00 Porto Alegre, RS, Brazil

<sup>c</sup> Liege University, Gembloux Agro-Bio Tech, TERRA Teaching and Research Centre, Animal Sciences, Passage des Déportés 2, 5030 Gembloux, Belgium

## HIGHLIGHTS

- We investigated the impacts of grazing intensity in an 18-year soybean-pasture ICLS.
- Simulations with the model STICS allowed to study climate change impacts.
- Total system production increased with grazing intensity.
- Pasture grazing increased SOC contents compared to the ungrazed treatment.
- Moderate grazing was best for climate change adaptation and mitigation.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

Editor: Elena Paoletti

### Keywords:

Integrated crop-livestock systems  
Climate change  
Resistance  
Productivity  
Soil organic carbon  
Crop model

## ABSTRACT

Integrated crop-livestock systems (ICLS) are proposed as key solutions to the various challenges posed to present-day agriculture which must guarantee high and stable yields while minimizing its impacts on the environment. Yet the complex relationships between crops, grasslands and animals on which they rely demand careful and precise management. In this study, from a 18-year ICLS field experiment in Brazil, that consists in annual no-till soybean-pastures grazed by beef cattle, we investigated the impacts of contrasted pastures grazing intensities (defined by sward heights of 10, 20, 30 and 40 cm, plus an ungrazed treatment) on the agroecosystem productivity and soil organic carbon (SOC) under both historical and future (2040–2070, RCP8.5) climatic conditions. We used an innovative methodology to model the ICLS with the STICS soil-crop model, which was validated with field observations. Results showed that the total system production increased along with grazing intensity because of higher stocking rates and subsequent live weight gains. Moderate and light grazing intensities (30 and 40 cm sward heights) resulted in the largest increase in SOC over the 18-year period, with all ICLS treatments leading to greater SOC contents than the ungrazed treatment. When facing climate change under future conditions, all treatments increased in productivity due to the CO<sub>2</sub> fertilization effect and the increases in organic amendments that result from the larger stocking rate allowed by the increased pasture carrying capacity. Moderate grazing resulted in the most significant enhancements in productivity and SOC levels. These

\* Corresponding author at: Passage des Déportés 2, 5030 Gembloux, Belgium.

E-mail address: [mathieu.delandmeter@uliege.be](mailto:mathieu.delandmeter@uliege.be) (M. Delandmeter).

improvements were accompanied by increased resistance to both moderate and extreme climatic events, benefiting herbage production and live weight gain. Globally, our results show that adding a trophic level (i.e. herbivores) into cropping systems, provided that their carrying capacities are respected, proved to increase their ability to withstand climate change and to contribute to its mitigation.

## 1. Introduction

Over the past decades, agriculture experienced a huge and nearly universal specialization due to multiple drivers such as globalization, industrial development and liberalization of trade that calls for economies of scale (Garrett et al., 2020). Empowered by the great promises offered by inputs used in large quantities during the green revolution, crop and livestock production systems have been largely decoupled throughout the world in most developed regions (Mazoyer and Roudart, 2002). But this specialization was associated to serious negative societal and ecological outcomes, such as degraded water quality, biodiversity loss, pesticide poisoning of humans and non-target species, soil erosion or greenhouse gas emissions (Naylor et al., 2005; Verhoeven et al., 2006; Power, 2010; Foley et al., 2011). Moreover, the growth in production facilitated by this approach relied, among other factors, on high levels of fossil fuels use, such as those associated with nitrogen fertilizer production, food and feed transportation and mechanization (Liu et al., 2010; Garrett et al., 2020). However, these expenses exhibit considerable volatility, as they are contingent on non-renewable resources and susceptible to energy market dynamics (Mazoyer and Roudart, 2002). Additionally, these costs tend to escalate during occurrences of extreme events, such as epidemics, droughts, floods, and wildfires (Wen et al., 2021), all of which being projected to increase in frequency in the future with a high level of confidence (IPCC, 2022).

To address these issues, integrated crop and livestock systems (ICLS) are increasingly proposed as key solutions to maintain high levels of food production while minimizing the agricultural impacts on the environment (Bonaudo et al., 2014; Lemaire et al., 2016; Garrett et al., 2020). They rely on the natural and long-established complementarities between crops and livestock: animals eat and convert forage and crop products, by-products and residues that are inedible for humans while they contribute to maintain soil fertility throughout manure production and habitats for auxiliaries in the agroecosystem through grazing lands. These complementarities might be harnessed across different spatio-temporal scales under various forms, each adapted to specific social and pedoclimatic contexts (Russelle et al., 2007; Herrero et al., 2010; Bell and Moore, 2012; de Moraes et al., 2014). ICLS can be organized at various scales, ranging from within the farm, with pastures or cover crops grazing, to beyond the farm level with exchanges such as manure, grain and straw within local groups of farmers (Martin et al., 2016). Including the animals into cropping systems allows to enhance nutrient cycling and functional diversity, helping e.g. for weed, pests and diseases control (Lemaire et al., 2016; Bonaudo et al., 2014). Among the associated socio-economic benefits, we find better farm productivity, income diversification, resilience to prices volatility and decreasing dependence on external inputs (de Albuquerque Nunes et al., 2021; Bonaudo et al., 2014; Bell et al., 2014).

Climate change poses additional threats on agricultural systems, notably due to the increasing frequency, intensity and duration of heatwaves, droughts and rainfall events (IPCC, 2019). There is strong evidence that higher ecosystem biodiversity increases their resistance and resilience to climate extremes thanks to the complementarities of the different trophic levels (Isbell et al., 2015; Di Falco and Chavas, 2008; Lin, 2011; Gaudin et al., 2015). However, there is still little knowledge on the impact of adding a trophic level (i.e. herbivore animals) in cropping systems on their stability and resistance. Domestic herbivores play a critical role in the carbon cycle (Soussana and Lemaire, 2014), and it was shown that the accumulation of soil organic matter can enhance the capacity of an ecosystem to recover from various

disturbances such as droughts, floods or fires (Franzluebbers, 2010). It is suggested that ICLS encourage farm resilience to climate change through larger farm productivity, income diversification, nutrient cycling and economic risk mitigation (Thornton and Herrero, 2015; Sekaran et al., 2021). But the agronomic and environmental responses of such systems to changing climatic conditions have not been evaluated yet. de Albuquerque Nunes et al. (2021) and Peterson et al. (2020), respectively based on a long-term field experiment and on its mechanistic simulation, indicated that integrating livestock into soybean systems improves their long-term yields stability and resilience, providing a buffer against climate stress. Yet questions remain regarding the soil-crop-animal interactions that are driving these results, and in which conditions and under which management these interactions are favored. In that perspective, crop modelling appears as a relevant tool to investigate the performance and impacts of contrasted ICLS, differing by the crops in the rotation and the level of livestock integration under diversified pedoclimatic conditions (Rai et al., 2022). Process-based models support multi-criteria analyses and allow a granular analysis of the different mechanisms that drive productivity and environmental indicators (Bassu et al., 2014; Asseng et al., 2019; Leng and Hall, 2019; Smith et al., 2020).

In this paper, we simulate and compare various ICLS under historical and future climatic conditions. An 18-year ICLS field experiment consisting in soybean-pastures grazed by cattle beef, with contrasting grazing intensities, was used to validate our simulation methodology. The objectives of this study are (i) to establish the methodology to model the grazing process with STICS, simulated by sward cuts on one side and dung and urine depositions on the other, and to compute the associated livestock live weight gain, (ii) to compare, under historical climatic conditions, the total productivity of the system, considering soybean, herbage and beef cattle live weight gain, resulting from the contrasted grazing intensities and the presence or absence of animals, but also their impacts on soil organic carbon, and (iii) to investigate, under projected future climatic conditions, their capacities of adaptation to climate change (productivity, stability and resistance) and mitigation (carbon sequestration).

## 2. Material and methods

### 2.1. Field experiment

The experimental site is located at Espinilho farm, in São Miguel das Missões district, Rio Grande do Sul State, Southern Brazil (28°94'19"S latitude, 54°35'11"W longitude, 465 m a.s.l.). The region has a warm, humid subtropical climate with an average annual temperature of 19 °C and precipitation of 1850 mm (Peterson et al., 2019). The soil is a clayey oxisol, Rhodic Hapludox (Soil Survey Staff, 1999), deep and well-drained with clayey texture (540, 270 and 190 g kg<sup>-1</sup> of clay, silt and sand, respectively).

The area has been managed since 1993 as no-till soybean in summer and black oat non grazed cover crop in winter. In 2001, an experiment conducted over 22 ha started as an integrated soybean-beef cattle annual rotation with a mixture of black oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pastures during winter and soybean (*Glycine max.* (L.) Merr.) during summer. Soybean management remained quite similar between treatments. In Rio Grande do Sul, soybean is usually sown in November and harvested in April, with flowering occurring in December–January (Zanon et al., 2016).

Treatments consisted of four different grazing intensities defined by

contrasting sward heights under continuous stocking (respectively 10, 20, 30 and 40 cm, denoted G10, G20, G30 and G40) and an ungrazed control treatment, denoted UG (de Albuquerque Nunes et al., 2021). The 12 experimental paddocks (three replicates for each treatment) ranged from 0.8 to 3.6 ha. To ensure that sward height remained close to the target, grazing management consisted in maintaining three tester animals per paddock continuously during the stocking period, plus a variable number of put-and-take animals adjusted on a monthly basis (Kunrath et al., 2020). Grazing usually started in June–July, with an initial sward height of  $24 \pm 4$  cm, and lasted for  $124 \pm 16$  days. Average stocking rates used to maintain target sward heights throughout the stocking period were 376, 651, 948 and 1331 kg of live weight  $\text{ha}^{-1}$  from light to intense grazing, respectively. Experimental animals were crossbred Angus  $\times$  Hereford  $\times$  Nelore steers with an initial body weight of  $210 \pm 23$  kg and 12 months of age on average (de Albuquerque Nunes et al., 2021).

## 2.2. Weather data

Historical weather data were collected by a station located at the experimental site. For the future climatic conditions, we selected the period 2041–2058, under the Representative Concentration Pathway (RCP) 8.5, to evaluate the impacts of an average global temperature increase of  $\sim 2$  °C (relatively to 1986–2005). Such a value is usually achieved under RCP8.5 at the horizon 2040–2070 or under RCP4.5 at the horizon 2070–2100 (IPCC, 2013). We selected the period of time 2040–2070 and the RCP8.5 in order to allow the comparison of our results with other similar studies such as Peterson et al. (2020). Future meteorological conditions (temperature, solar radiation, precipitation, atmospheric CO<sub>2</sub> content) for the years 2041–2058 were provided by Peterson et al. (2020), based on an ensemble of 6 CMIP5 Global Climate Models using RCP8.5 with very high greenhouse gas emissions (IPCC, 2014).

Daily rainfall and temperatures, averaged over each month of the two periods 2001–2018 and 2041–2058, are shown on Fig. A1. In the future period 2041–2058, compared to the historical 2001–2018 period, the average total annual rainfall increases from 1699 mm to 2318 mm. But this would be contrasted between seasons, with an increase of rainfall in summer (+57 %) but a decrease in winter (–26 %). The average yearly temperature is projected to rise from 20.4 °C in historical climatic conditions to 23.0 °C in the future. The absolute increase will be higher over summer months (+4.01 °C) than winter (+1.75 °C). The atmospheric CO<sub>2</sub> content also increases, from 385 ppm to 575 ppm. Of paramount importance, it is anticipated that forthcoming climatic conditions will lead to a heightened occurrence of extreme events, including floods and droughts (IPCC, 2014), which is addressed in Section 2.5.

## 2.3. The soil-crop model STICS

We used the standard version 10 of STICS (*Simulateur multi-disciplinaire pour les Cultures Standard*). STICS is a soil-crop model which computes changes in agronomic (e.g. biomass and yield) and environmental variables (e.g. soil organic carbon, nitrate leaching, soil water and nitrogen, etc.) from input variables and parameters relating to weather conditions, soils and cropping systems (Brisson et al., 2009). It is a process-based model that simulates plant growth as well as the flow of water, C and N fluxes. To simulate soil C and N mineralization, it is based on the AMG model (Clivot et al., 2019). Chaining simulations across years is used to model trends and impacts across long-term rotations, encompassing both crops and grasslands.

Increasing atmospheric CO<sub>2</sub> concentration due to climate change acts to enhance the radiation use efficiency (RUE) through an exponential factor. The rate of increase for this factor mainly varies with the plant metabolism (C<sub>3</sub>/C<sub>4</sub>). The projections that we used for the weather data over the period 2041–2058 predict a CO<sub>2</sub> concentration of 575 ppm, which induces an 18 %-increase of RUE for both pastures and

soybeans. The model also considers a decrease in stomatal conductance that is proportional to the increase in RUE (Brisson et al., 2009).

## 2.4. Livestock integration into the soil-crop model

Grazing animals are not explicitly included in the STICS model. Between the beginning and the end of the grazing period, to mimic the grazing process, we simulated successive cuts at time intervals based on the observed averaged return time of animals on a same grass tiller, with a first constraint: (i) the time between two successive cuts had to be close to the resting period observed on the field between two successive bites on the same tiller, from 7 days for G10 to 30 days for G40 (P. Carvalho, personal communication). The remaining sward height after a cut is a parameter of the model. It was manually set in a manner that the average height between two cuts is close to the observed sward height (Table A1 and Fig. A2), with a second constraint: (ii) the sward height remaining after a cut had to be realistic considering that the cuts simulate a steer bite and that, on average, steers remove about 50–55 % of the canopy height at each bite (Laca et al., 1992). The parameters that we used are available in Table A1. Similarly to field observations, the total herbage production (THP) was computed as the sum of initial herbage mass and the herbage accumulation rate from all subperiods (Kunrath et al., 2020).

For simulating the animal excreta on the pasture (dung and urine), we used the methodology proposed by Graux et al. (2020). At each cutting event, liquid manure and urea are spread, simulating animal faeces and urine. Nitrogen (N) amount associated to animal faeces is a linear function of the biomass that was removed by the cuts, which represents animals dry matter intake (DMI). The total quantity of animal faeces is derived from the N quantity, assuming that the N content in faeces is constant. Finally, the C:N ratio of animal faeces is derived from plant N concentration the day before the cutting event. N quantity in urine is computed as animal N intake minus N lost in faeces and N retained for growth. Only two parameters, relating to the linear relationships between DMI and animal faeces N and urine N were respectively modified: the first according to de Souza Filho et al. (2019), that measured steers individual DMI and fecal production; and the second considering that animals in our experiment are growing beef cattle and not dairy cows (such as simulated by Graux et al., 2020). All modelling equations and further details to compute C and N amount of animal excreta are available in Appendix B.

Live weight (LW) gain of the animals was computed from total herbage production following the relationship of Fig. A3. Based on the field observations of de Albuquerque Nunes et al. (2021), we linked the observed total herbage production ( $\text{kg DM ha}^{-1}$ ) - i.e. the herbage available for grazing measured with exclusion cages (Kunrath et al., 2020; Klingman et al., 1943) - with the observed total live weight gain per hectare ( $\text{in kg LW ha}^{-1}$ ). The ratio between the two is known as the Forage Conversion Ratio (FCR). This ratio decreases with decreasing grazing intensities (Fig. A3), meaning that lower stocking rates induce forage losses.

## 2.5. Systemic indicators

The total productivity of the system was computed following three axes. Firstly, we considered (i) the agronomic production as the sum of herbage production and soybean production (both expressed in T DM  $\text{ha}^{-1}$ ). Secondly, we investigated (ii) the food-related energetic production through the sum of nutritive values of meat and soybean for humans (expressed in kcal  $\text{ha}^{-1}$ ). Finally, (iii) the economic values of production were considered through the gross profit, i.e. the sum of meat and soybean production (expressed in USD  $\text{ha}^{-1}$ ).

Concerning the nutritive value of live weight gain, we considered that 1 kg of live weight gain was equal to 0.83 Mcal, taking into account (i) a dressing percentage, i.e. the ratio of carcass weight over total live weight, equal to 52 % (reported in our field experiment by Aguinaga

et al. (2006)), (ii) that, in average, 62.73 % of this carcass is available for retail product (Diles et al., 1996), and (iii) that 1 kg of beef meat, i.e. the retail product, is equal to 2.54 Mcal (USDA, 2019). For soybeans, we considered that 1 kg of grain yield was equal to 4.7 Mcal (USDA, 2019).

Regarding profitability, operational costs of soybean, pastures and livestock operations were taken into account, altogether with grain and animal sales. Costs and revenues were calculated using historical market sale prices. Livestock operational costs and opportunity costs of capital were specific to each ungrazed and ICLS treatment, whereas soybean costs were considered as constant between treatments given that crop management was similar. The whole computational methodology for this third metric was adapted from de Albuquerque Nunes et al. (2021). Both costs and revenues from grain and animal products were considered constant even in the future climatic scenario, in order to avoid economic hypotheses within productivity comparisons.

To study the adaptation of assessed systems to climate change, we considered the evolution of the total productivities of the systems, but also their stability and resistance against extreme climatic events projected for the period 2041–2058 under RCP8.5.

Following the definition of Isbell et al. (2015), the stability of the agroecosystem productivities, namely total herbage production, soybean yield and live weight gain, were computed as the ratio of their respective mean productivity ( $\mu$ ) over their respective standard deviation ( $\sigma$ ):

$$\text{Stability} = \frac{\mu}{\sigma} \quad (1)$$

Stability indicators are dimensionless and thus directly comparable between different levels of productivity. Yet, considering concomitantly the standard deviation and the mean productivity within the stability indicator remains of importance to avoid penalizing hypothetical systems that would be relatively unproductive but might be considered as ‘stable’ in the sense that their (low) yields would not vary much.

As defined by Isbell et al. (2015), resistance represents the ability for an agroecosystem to retrieve productivity levels close to normal after a climatic event. Following Isbell et al. (2015), to characterize the years as ‘normal’ or ‘moderately’/‘extremely’ dry or wet, we rely on the Standardized Precipitation-Evapotranspiration Index (SPEI) drought index. The SPEI, which characterizes the onset, duration and magnitude of a drought based on the difference between precipitations and evapotranspiration (Vicente-Serrano et al., 2010), was computed for each month out of the 18-year period. Potential evapotranspiration was calculated based on Penman’s formula (Penman, 1948). The SPEI therefore captures the impact of temperature on water demand.

A time scale of 3 months was used, meaning that for each month, the SPEI-3 index was based on the water balance of the concerned month and the two preceding ones. More precisely, each cropping season was characterized according to the 3-month period preceding its harvest (usually February–April for soybean and September–November for pasture). The 3-month time scale was selected as the best compromise to cover the average period from the flowering of soybean to its harvest (~3 months), the most sensitive period for stress to impact soybean grain filling (~ last 2 months), the whole growing season of pasture (~6 months) and the active grazing period (~4 months) (Sionit and Kramer, 1977; Zanon et al., 2016; Poudel et al., 2023). As an example, following the definition of the SPEI index, a value of SPEI-3 of  $-1.28$  for the month of April 2005 corresponds to a 3-month drought (as indicated by the negative value) that has only occurred once per decade during the months of February to April over the period 2001–2018 (Isbell et al., 2015).

In a second time, we identified climatic events as ‘extreme’ if they occurred less than once per decade, i.e.  $<10\%$  of time (below quantile  $q_{0.1}$  for extreme dry events and above quantile  $q_{0.9}$  for extreme wet events). Similarly, they were identified as ‘moderate’ if they occurred between once out of four years and once per decade (between quantiles  $q_{0.1}$  and  $q_{0.25}$  for moderately dry and between quantiles  $q_{0.75}$  and  $q_{0.9}$  for

moderately wet events). Periods that were neither moderate nor extreme were categorized as ‘normal’.

Finally, in order to compute the SPEI-3 index for the future period 2041–2058, we used the same coefficients of the distribution that were obtained under the historical period 2001–2018. Indeed, the aim remains to characterize the changes in dry and wet events relatively to the current climatic conditions. In the same way, for categorizing these future events, we used the same quantiles that were computed over the historical period. Results of the characterization of climatic years are shown in Fig. 1.

Following the definition of Isbell et al. (2015), resistance was finally computed as

$$\Omega = \frac{\bar{Y}_n}{|Y_e - \bar{Y}_n|} \quad (2)$$

with  $\bar{Y}_n$  the mean productivity during normal years and  $Y_e$  the productivity during an extreme event (moderately/extremely wet/dry).

## 2.6. Model parameterization, calibration and validation

Soil parameters were initially retrieved from SoilGrids maps of soil properties (Poggio et al., 2021), with pedotransfer functions from the R package *eupf2* (Szabó et al., 2021). Some soil parameters related to soil water content and soil organic carbon were then manually adapted according to field observations.

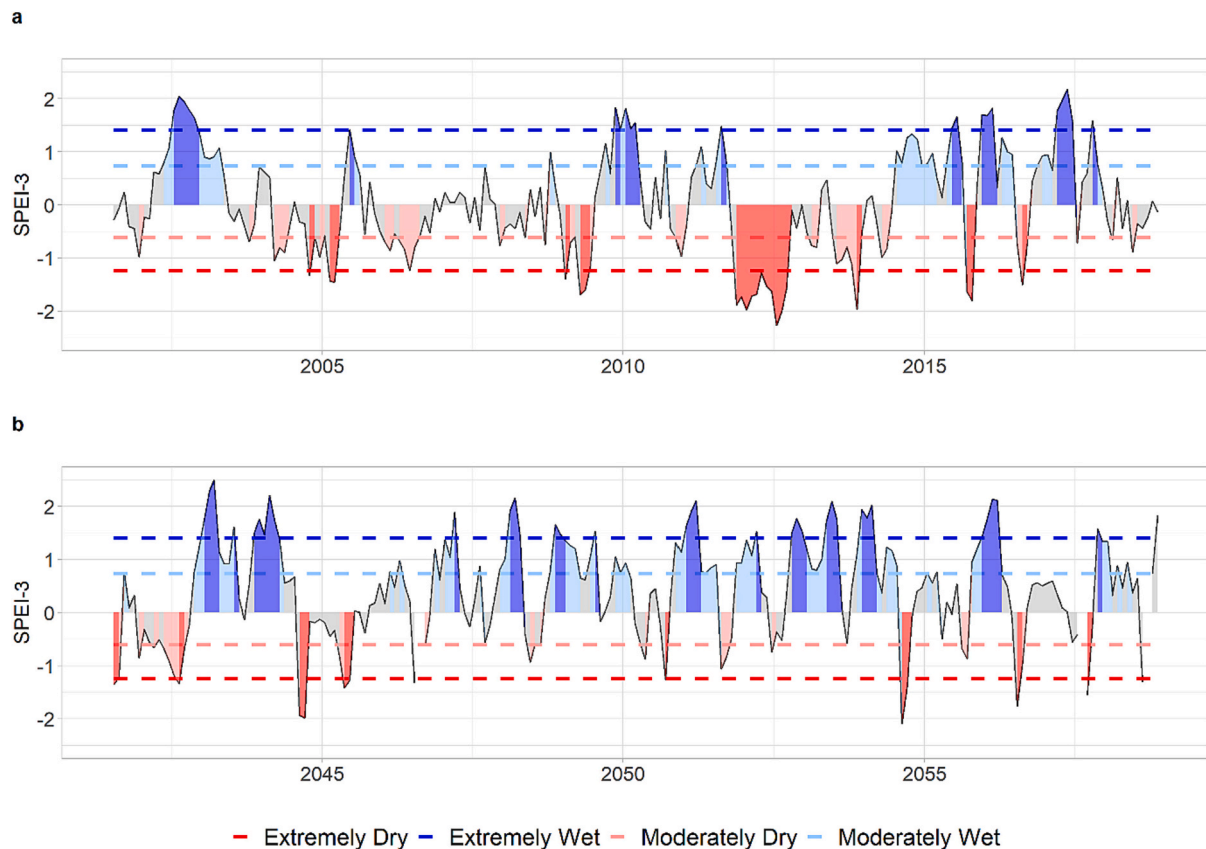
For the modelling of soybeans, we started with the standard plant file of the STICS model (Beaudoin et al., 2022). Parameters used to compute root system growth are based on the future standard parameter file for pea (L. Strullu, personal communication). The parameterization was adapted according to data available for another field experiment in Brazilia (Brazil) (Kothari et al., 2022). We slightly modified some cardinal temperatures. The base temperature at which growth starts was increased from  $4^\circ\text{C}$  to  $9^\circ\text{C}$ , in agreement with Kothari et al. (2022) that simulated soybean development with several crop models and used values ranging from  $7$  to  $10^\circ\text{C}$ , and in concordance with the field experiment of de Souza et al. (2013) that reported a base temperature of  $10^\circ\text{C}$ . Still following de Souza et al. (2013) and Kothari et al. (2022), the temperature above which foliar growth stops was decreased from  $45^\circ\text{C}$  to  $38^\circ\text{C}$ . Finally, the maximal temperature above which grain filling stops was increased from  $30^\circ\text{C}$  to  $32^\circ\text{C}$ , in accordance with the chamber experiments of Boote et al. (2018) and Alsajri et al. (2020). Based on these changes, radiation use efficiencies and thermal times between crop development stages were slightly adapted (Table A2).

For the pasture, we used the standard parameters for Italian ryegrass, that were modified considering also that the pasture is actually composed of black oat seeded into ryegrass which naturally regrows from one season to another (Table A2). Parameters used to compute root system growth of pasture are based on the future standard parameter file (Graux et al., in prep.).

To evaluate the accuracy of the model simulations based on the historical records, three indicators were concomitantly used (Beaudoin et al., 2008): the Root Mean Square Error (RMSE), the Model Efficiency (EF) and the Normalized Deviation (ND):

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{Y}_i - Y_i)^2}$$

$$\text{EF} = 1 - \frac{\sum_{i=1}^n (\hat{Y}_i - Y_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2}$$



**Fig. 1.** SPEI-3 index (expressing the dryness/wetness), computed for each month for a) the historical period 2001–2018 and b) the future period 2041–2058 (RCP8.5). The colors designate the category of climatic events (extremely/moderately dry/wet). Dashed lines refer to the quantiles  $q_{0.1}$ ,  $q_{0.25}$ ,  $q_{0.75}$  and  $q_{0.9}$ , which determine the category of climatic events.

$$ND = \frac{\sum_{i=1}^n Y_i - \sum_{i=1}^n \hat{Y}_i}{\sum_{i=1}^n Y_i}$$

with  $\hat{Y}_i$  the simulations and  $Y_i$  the observations. We consider that the model is adequate when  $EF \geq 0.5$  and  $|ND| \leq 0.1$  (Beaudoin et al., 2008).

### 3. Results

#### 3.1. Pasture, crop and livestock productivity

Simulated sward heights during the stocking period were close to targeted heights and close to field observations (Fig. A4). The model successfully simulated the total herbage production (Fig. 2a and b), live weight gain (Fig. 2c and d) and soybean grain yield (Fig. 2e and f), with EF being above the 0.5 threshold and ND being lower to 0.1 in absolute value, for the three variables (Fig. 2a, c and e). No contrasted trend between grazing treatments were reported which guarantees that further differences in treatments comparisons will not be due to model bias. We see with the distributions of THP (Fig. 2b), live weight gain (Fig. 2d) and soybean yield (Fig. 2f) that the model was able to reproduce the productivity trends between the treatments, with no significant difference between observations and simulations ( $p < 0.05$ ).

Considering dung and urine depositions appeared to be essential in the simulation process (Fig. A5). They allowed to simulate a total herbage production that is larger for the grazed treatments G20, G30 and G40 than for the ungrazed treatment. Accurate estimation of pasture production was also a critical point for accurate live weight grain simulations.

Our simulations established a lower THP for G10 and UG treatments compared to G30 and G40 ( $p < 0.05$ ; Table A3). The model reproduced the same hierarchy in THP than what was observed on the field:  $G40 > G30 > G20 > UG > G10$  (Fig. 4a), with the ungrazed treatment production being lower than for intensities G20, G30 and G40 (Kunrath et al., 2020; de Albuquerque Nunes et al., 2021).

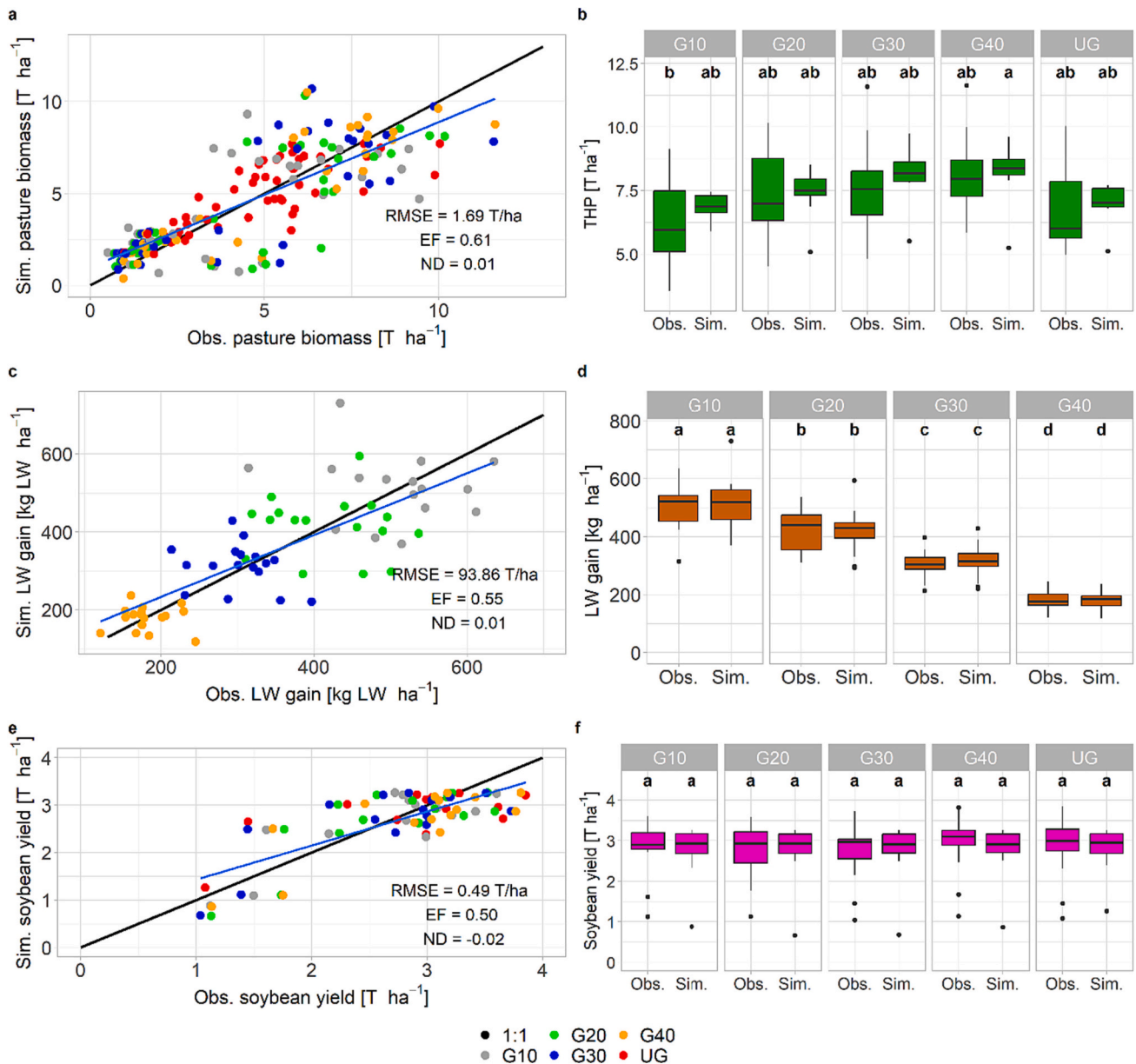
On the other hand, total live weight gain per hectare increased with grazing intensity ( $p < 0.05$ ; Fig. 2d and Table A3), inducing a gross profit that increased with the inclusion of animals into the system and with grazing intensity.

Concerning soybean yields, the model did not simulate any significant difference between treatments ( $p > 0.05$ ; Fig. 2f and Table A3), similarly to the results of field observations (Peterson et al., 2019).

Total system production, in terms of gross productivity in tons per ha, followed the same hierarchy than THP (Fig. 3a). But when expressed in nutritive (Fig. 3b) and economic (Fig. 3c) values, because of the different conversion coefficients that result from these metrics, the live weight production associated with the pastures grazing induced an increasing total system production with increasing grazing intensity, the difference being exacerbated and significant ( $p < 0.05$ ) when US Dollars was used as metric (Table A4).

#### 3.2. Soil organic carbon

Globally, the soil organic carbon increased in all treatments over the whole 18-year period (Fig. A6). Losses of carbon were occurring during the soybean phase but were compensated by the storage of C during the pasture season, which storage was systematically slightly bigger than the previous loss. Moderate and light grazing (G30 and G40 treatments) appeared to increase the most the soil organic carbon content (Fig. 4), the difference being more marked over the whole soil horizon



**Fig. 2.** Goodness of fit results for a) pasture biomass, b) total herbage production (THP) distribution, c) cattle live weight (LW) gain, d) cattle live weight gain distribution, e) soybean grain yield and f) soybean grain yield distribution. For the variables distributions, only the years for which observations were available for all five treatments were used. Letters refer to groups statistically different ( $p < 0.05$ ). G10, G20, G30 and G40 refer to the grazing intensity treatment, and UG designates the ungrazed treatment.

considered by STICS (Fig. 4b). Grazed pastures globally allowed to increase soil organic carbon compared to the ungrazed treatment.

### 3.3. Adaptation to climate change

#### A. Productivity

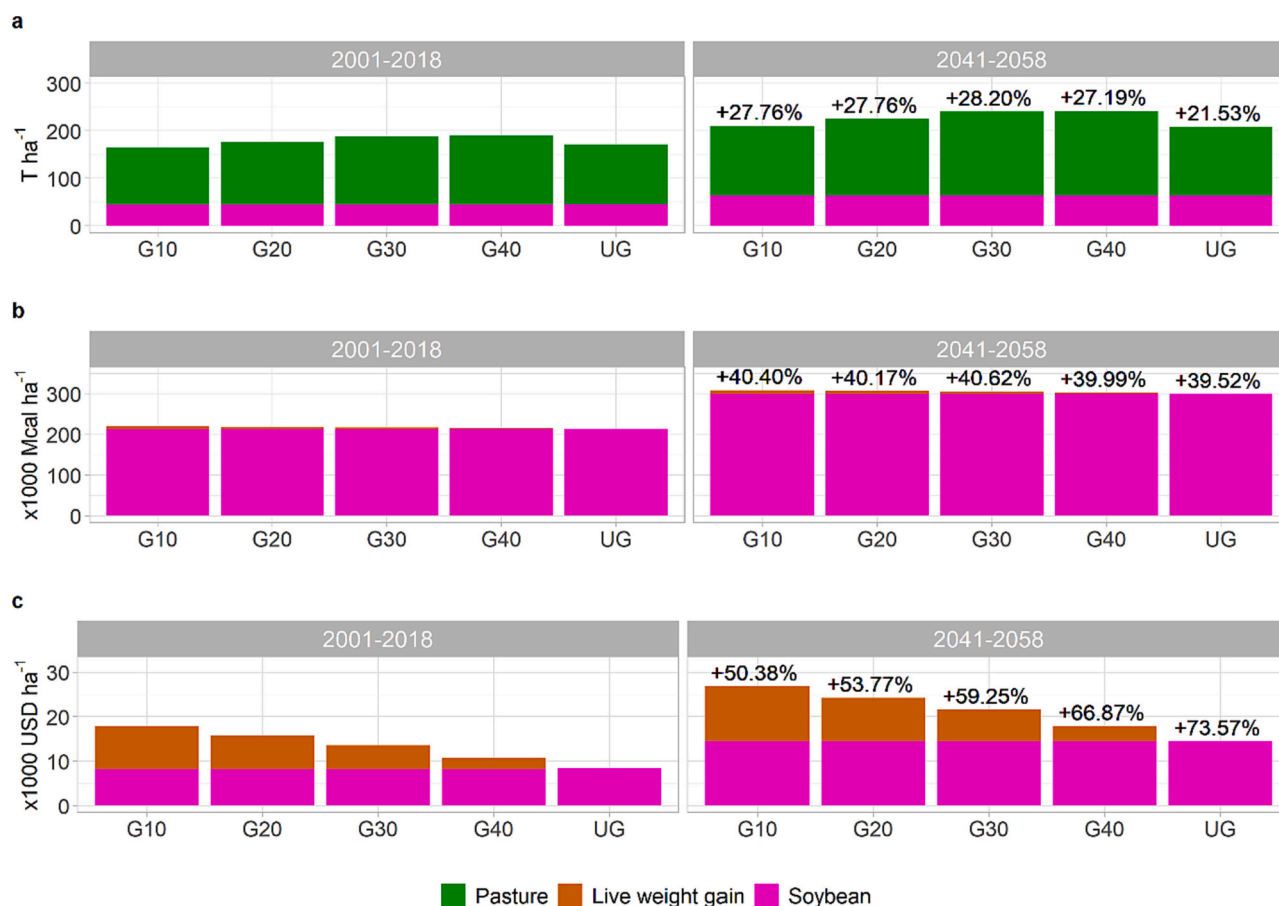
Globally, the total productivity of the system is expected to increase in the future (period 2041–2058) under the climate change scenario RCP8.5 (Fig. 3, Tables A3, A4 and A5). Average soybean grain yield would significantly raise ( $p < 0.05$ ) from 39.52 % (UG) to 41.05 % (G10). No substantial differences in these increases were noticed between treatments (Table A3).

For herbage production and live weight gain, moderate to light grazing intensities productions would increase the most. Average herbage production would significantly increase for all treatments ( $p$

$< 0.05$ ), from 22.75 % (G10) to 24.14 % (G30), but with a smaller amelioration for the ungrazed treatment (+15.04 %; Tables A3 and A5). The relative increases in the economic productivity would be even larger (up to 38.49 % for the live weight gain and up to 77 % for the soybean), given that we assumed fixed operational and opportunity costs. Similarly, live weight gain would also significantly increase ( $p < 0.05$ ) for ICLS treatments, except for the light grazing (G40) treatment (Table A3).

However, if the average productivity of herbage would increase in the future, this would also often be associated with greater inter-annual variability (up to +18 % in THP standard deviation for the G30 treatment; Table A3 and Fig. A7). In the other direction, for soybeans, inter-annual yields variability would also decrease with climate change (up to –30 % in soybean grain yield standard deviation for the G30 treatment; Table A3 and Fig. A7).

#### B. Soil organic carbon



**Fig. 3.** Total productivity expressed in terms of a) biomass production [ $T\ ha^{-1}$ ], b) nutritive value [ $Mcal\ ha^{-1}$ ] and c) economic value [ $US\ dollars\ (USD)\ ha^{-1}$ ], under historical (2001–2018) and future (2041–2058, RCP8.5) climatic conditions. For each treatment, productivity gains in the future period 2041–2058 are written in percents, relatively to the historical period 2001–2018. G10, G20, G30 and G40 refer to the grazing intensity treatment, and UG designates the ungrazed treatment.

As for crop production, SOC content is expected to increase during the period 2041–2058, and the increase is expected to be greater than the one observed during the historical period (Fig. 4). For the different treatments G10, G20, G30, G40 and UG, SOC augmentation would respectively be 75 %, 104 %, 79 %, 87 % and 45 % larger during the period 2041–2058 compared to the historical period 2001–2018, for the soil horizon 0–30 cm. Over the whole soil profile, these differences would respectively be 61 %, 69 %, 61 %, 63 % and 40 % for the treatments G10, G20, G30, G40 and UG. Hence it is the G20 treatment that experienced the highest SOC augmentations when comparing the two periods of time. As for the historical period, the increases in SOC under the climate change scenario would be greater for moderate and light grazing intensities over both the 0–30 cm (G30: +10.14 %, G40: +10.20 %) and the whole soil (G30: +21.75 %, G40: +22.91 %) horizons.

Compared to the intense grazing treatment (G10), moderate to light grazing (G30 and G40) appeared to sequester carbon into the soil at deeper horizons when evaluating the percentage of soil organic carbon that was stored below 30 cm.

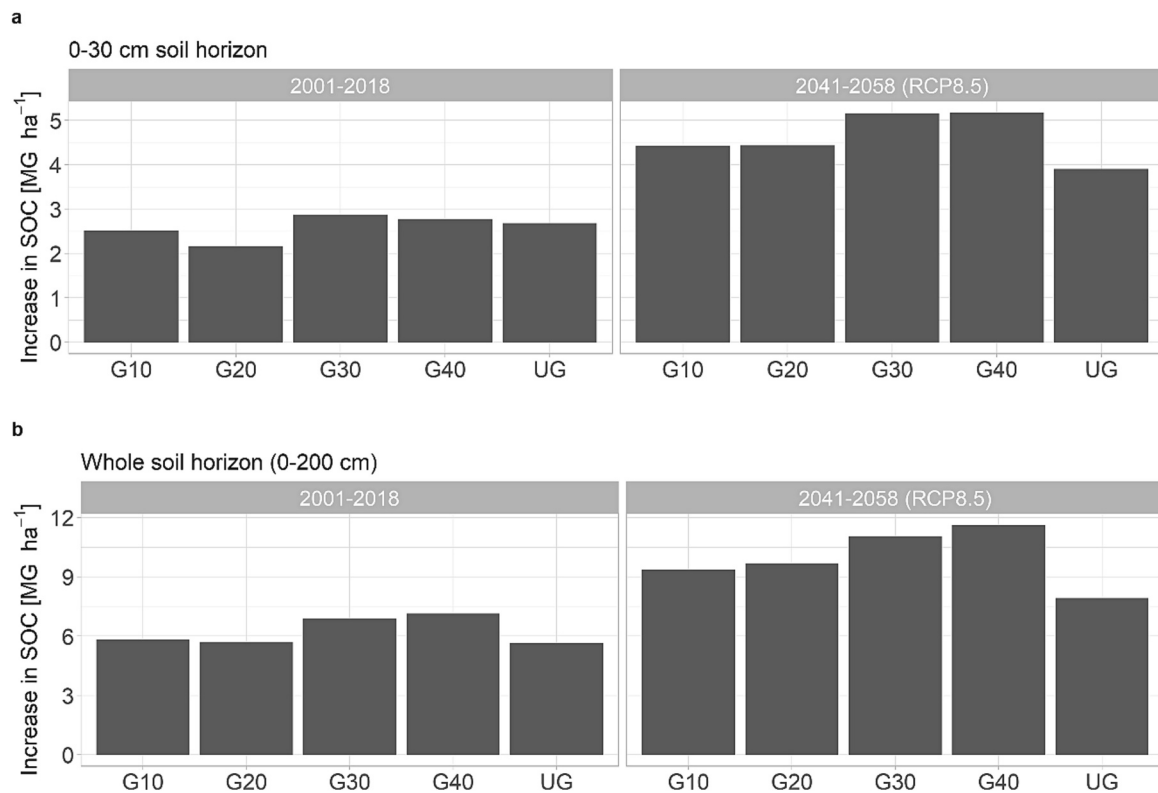
### C. Stability and resistance

The stability criterion computed over the three productivity variables are compared in Fig. A8. Concerning soybean grain yield (Fig. A8a), as expected with previous results, the model did not simulate much difference between treatments. Yet it suggests that soybean stability would increase when facing future climate change conditions. For total herbage production (Fig. A8b), the ungrazed treatment, which had low productivity levels (Fig. 3a), is expected to exhibit greater stability. Finally, for the live weight gain (Fig. A8c), whereas during the historical

period, the stability followed the same trend than productivity (Fig. 3c), it appeared that the stability would be similar between the different treatments for the period 2041–2058. This reveals that the larger live weight gain associated with higher grazing intensity comes with greater variability.

When analyzing the linear regressions between the productivity of soybean or herbage production on one hand and the SPEI-3 index on the other (Fig. 5), both herbage production and soybean yield were found to significantly increase with the SPEI-3 index ( $p < 0.05$ ). These results highlight the fact that wetter periods between September and November for pastures and between February and April for soybean are associated to higher production.

Resistance capacities to extreme and moderate climatic events during the future climatic conditions in 2041–2058 are respectively presented in Fig. 6 and Fig. A9. Concerning soybean, no substantial impact of grazing intensity was found on its resistance to moderate and extreme climatic events (Fig. 6a and Fig. A9a). Yet only one period was categorized as extreme for soybean (extremely wet). The ungrazed treatment exhibited a greater resistance for herbage production compared to the ICLS treatments (Fig. A9b and Fig. A6b). For the total herbage production and the live weight gain, within ICLS treatments, moderate and light grazing intensities (G30 and G40) showed greater resistance capacities to both moderate and extreme climatic events (Fig. A9b, Fig. A9c, Fig. 6b and Fig. 6c).



**Fig. 4.** Soil organic carbon (SOC) evolution over the 18-year period, as simulated under historical and future climatic conditions. Results are reported over a) the soil horizon 0–30 cm and b) the whole soil horizon considered by STICS (0–200 cm). G10, G20, G30 and G40 refer to the grazing intensity treatment, and UG designates the ungrazed treatment.

## 4. Discussion

### 4.1. The influence of metrics in crop-livestock systems productivity comparisons

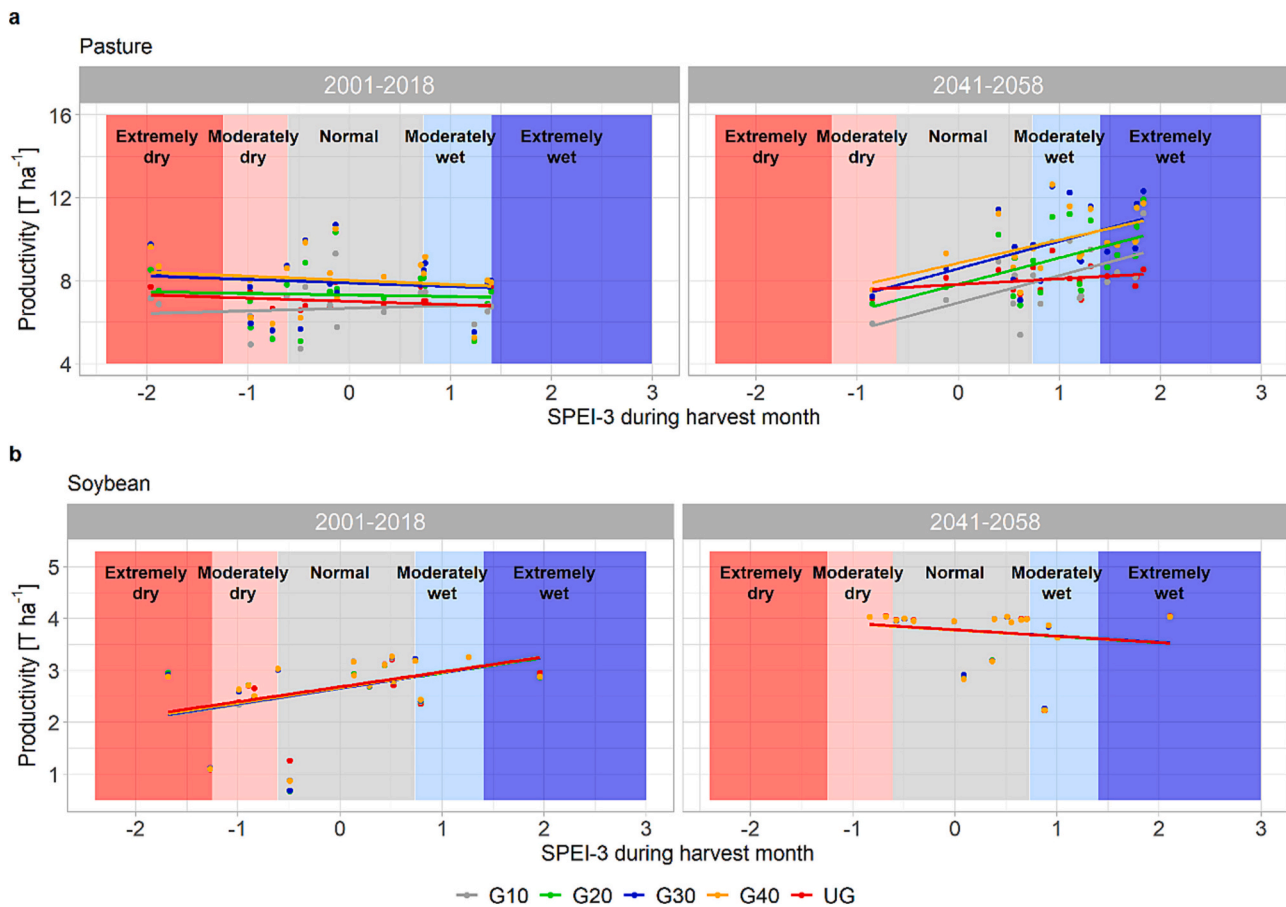
Global productivity comparisons between treatments differ according to the metrics that we considered. Expressed in tons per ha, the comparison of total herbage production and soybean grain yield highlighted the effect of grazing intensity on total herbage production, this last decreasing with increasing grazing intensity but yet being greater with light to moderate grazing intensities compared to the ungrazed treatment. When expressed in nutritive and economic values, the productivity of ICLS treatments showed to increase together with grazing intensity, underlining the sward valorization that herbivores allow.

Except for the more intensive grazing management (G10), the larger herbage production under all other ICLS is explained by the stimulation which the frequent defoliation performed by animals (simulated by cuts in our model) represents. In our methodology, each cut that simulates the grazing process *i*) reduces the leaf area index to certain levels computed from the residual sward height and *ii*) maintains the pasture in a vegetative process. The growth of LAI in the STICS model follows a logistic function of crop development stages (Brisson et al., 2009), being maximal at a certain development stage and then declining gradually as the plant approaches flowering stage. Therefore, in our grazing simulation, moderate grazing allows to observe a maximal LAI growth rapidly after a precedent cut, whereas overgrazing (G10), resulting in a low residual LAI, leads to an initial slow LAI growth rate (before the inflexion point in the logistic function). At the other extreme of the spectrum, low grazing intensity (G40) results in a high residual LAI, which leads to a rapidly declining LAI growth rate (after the inflexion point in the logistic function). The mechanistic modelling approach reproduces properly the stimulating impact of grazing on sward growth as it was observed on the field, which was explained by the extension of the

vegetative period of plants by sound herbivory without compromising its growth rates, while ungrazed pastures tend to present early internode elongation, flowering and also sometimes lodging (Kunrath et al., 2020). We also observed that the simulations exhibit a lower variability than field observations, especially for herbage production (Fig. 2b). We believe that this is due *(i)* to the deterministic propriety of the model, whereas field observations come from replicates into the field experiment design which induce further variability within each treatment; but also *(ii)* to the sensitive grazing organization of the field experiment, which requires to frequently adjust the number of grazing animals in order to maintain the targeted sward heights, whereas the model automatically performs regular cuts at the exact same height within each treatment.

Concerning soybean yields, the absence of significant difference between treatments is in line with the field experiment where yields were found to be similar between grazed and ungrazed paddocks. Yet, both the field experiment and our simulations suggest that soybean cultivated in ungrazed systems would lead to very slightly bigger yields than within the ICLS treatments (except for G40 in the field experiment), in agreement with Franzluebbbers et al. (2014) and with Brazilian farmers perceptions that grazing is detrimental to soybean production (Kunrath et al., 2020). This could be associated with lower soil water content and slower soybean maturation that are observed with winter grazing (Peterson et al., 2019; Kunrath et al., 2020). We believe that further calibration of soybean model parameters with granular field datasets would be helpful to better understand the impact of soil factors on soybean development.

From the nutritive perspective, our results showed that the calories provided by meat, considering the dressing percentage and the ratio of retail product, are almost negligible compared to soybean calories, but yet increase the nutritive value of ICLS compared to the ungrazed treatment (de Albuquerque Nunes et al., 2021). Moreover, using proteins as a metric could increase meat value relatively to soybean,



**Fig. 5.** Linear regression between the SPEI-3 index (expressing the dryness/wetness related to the 3 months preceding harvest) and the annual productivity of a) the pasture, i.e. the total herbage production, and b) the soybean grain yield. For readability, the intervals of confidence are not shown. G10, G20, G30 and G40 refer to the grazing intensity treatment, and UG designates the ungrazed treatment.

considering that animal-derived proteins are of higher nutritional value than plant-derived proteins (Peyraud and Peeters, 2016; de Albuquerque Nunes et al., 2021). The economic comparison suggests furthermore that the integration of livestock into cropping systems allows nowadays to boost the monetary profit in a considerable way (Russelle et al., 2007; Sekaran et al., 2021). The conversion of live weight gain into nutritive value and gross profit was however assumed to be constant between the treatments, while Aguinaga et al. (2006) suggested that meat quality was actually higher in moderate grazing intensities as compared to intensive and light ones. Indeed, both the body condition score and fat thickness showed a quadratic response with grazing intensities, pointing out the importance of considering not only total live weight gain per hectare but also animals' individual performances (Aguinaga et al., 2006). Considering this in our simulations could also lead to a quadratic response of total live weight gain per hectare (expressed in nutritive value and gross profit) to grazing intensity, as suggested by de Albuquerque Nunes et al. (2021).

#### 4.2. Pasture grazing helps to sequester carbon

The global increase in soil organic carbon for all treatments can be related to the absence of tillage and the incorporation of pasture into the rotation (Maia et al., 2010; Soussana et al., 2004). The oscillations in SOC that were predicted by the model, the SOC content increasing during the pasture phase and declining during the cropping phase, were also found in other pasture-crop rotations (Franzuebbers et al., 2014).

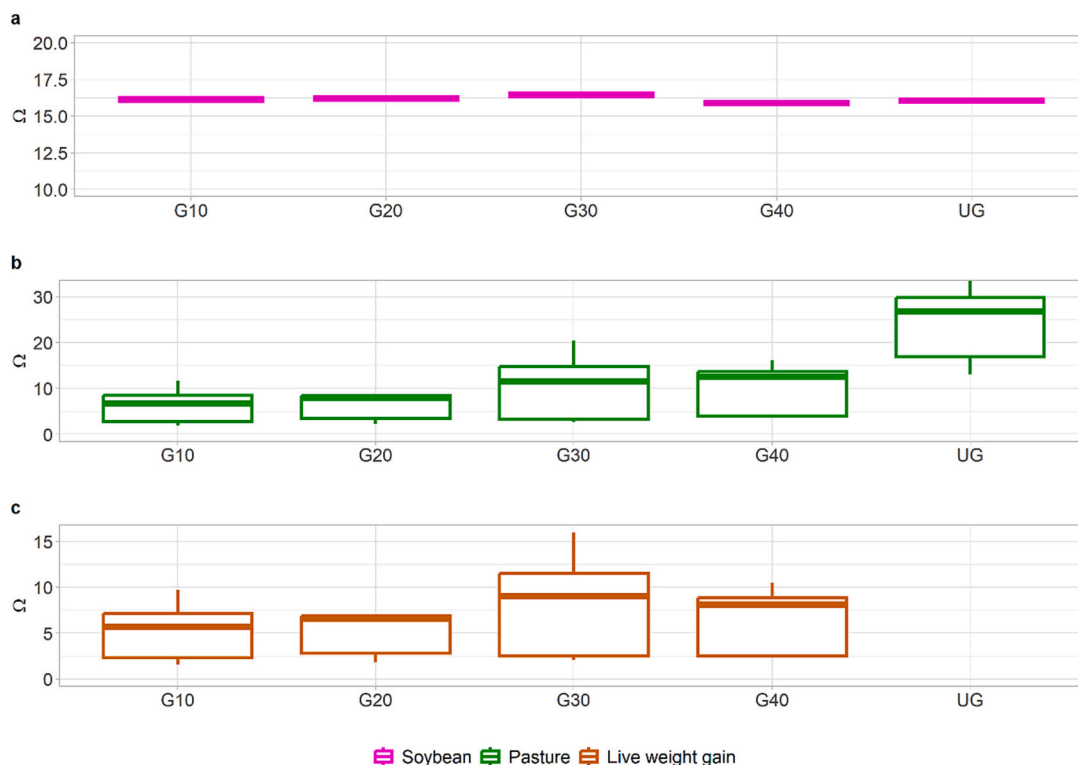
The positive effect of pasture grazing on SOC is explained by the greater biomass production that it allowed, notably through mineralization, and by the return to the soil of this biomass *i)* under the form of

manure and urine during grazing season or *ii)* as residue at the end of the season. This was already confirmed by numerous studies (IPCC, 2019; Tracy and Zhang, 2008) that explained the larger SOC positive evolution with grazing by greater aggregate stability and labile organic matter pools in near-surface soil depths (Liebig et al., 2012), stimulation of processes such as C cycling from aboveground plant litter to soil, aboveground production, root exudation and respiration rates, increased tillering, etc. (Liebig et al., 2005). Franzuebbers and Stuedemann (2008) also noticed, when comparing wheat-cover crop systems grazed by cattle or left unharvested, an increase in soil microbial biomass C with grazing.

The greater C sequestration under moderate and light grazing (G30 and G40) that we reported is in line with the conclusions of Cecagno et al. (2018) within the same field experiment. Based on a simulation of SOC from annual C inputs, they revealed a higher potential of C sequestration with G30 and G40 grazing intensities. This also agrees with Soussana and Lemaire (2014), who explained that overgrazing might impair C sequestration by negative impacts linked to excessive active N forms, with intensive grassland management lowering the C:N ratio of plant litter and thus leading to faster degradation and shorter residence time.

#### 4.3. Moderate grazing is best for adapting to and mitigating climate change

The overall increase of system productivity under the climate change scenario is mainly associated with the CO<sub>2</sub> fertilization effect, which increases the radiation use efficiency because of the greater atmospheric CO<sub>2</sub> content and modifies water and nutrient cycles (Kimball et al.,



**Fig. 6.** Resistance ( $\Omega$ , dimensionless) against the extreme climatic events of the period 2041–2058 (RCP8.5) for a) soybean grain yield, b) total herbage production and c) live weight gain. G10, G20, G30 and G40 refer to the grazing intensity treatment, and UG designates the ungrazed treatment.

2002). Yet we did not take into account potential changes in prices or nutritive values that could happen in the future, for instance because of a loss in grain or meat quality, nor potential pressures such as pests or diseases that are expected to increase in the future (IPCC, 2022). Potential plant damage due to violent winds or floods -such as foliage destruction or lodging- is also not considered by the model.

It appeared that soybean yield was very sensitive to the model parameter stopping grain filling over a threshold temperature. This parameter was set to 32 °C according to the literature, but we observed that if we changed it to 30 °C, average soybean yields would actually slightly decrease with even sometimes null yields (results not shown). Further sensitivity studies about the influence of elevated temperatures on crop development, phenology and yield would be therefore welcomed since the associated parameters have a strong impact on the evolution of crop productivity with climate change.

The future increase in pasture biomass also results from the good management that we consider in our simulations. Indeed, an increase in sward biomass induces a growth in the fertilization associated with the different cuts that simulate animals' dung and urine, since this is computed by the model from the biomass that is removed at each cut. We therefore simulate an increase in the stocking rate which is in accordance with the sward capacity. But this does not take into account potential stresses on animals that could induce, for example, a reduction of fertility and meat production (Sejian et al., 2018; Bernabucci, 2019).

Few studies evaluated the impact of climate change on soybean yields and temporary pastures biomasses, and even fewer within ICLS. Our climate change projections disagree with Peterson et al. (2020) that simulated with the APSIM model one ungrazed and one crop-livestock systems at the same site than in our study and which predicted average declines of 15 % for soybean yield and of 23 % for pasture biomass. But their simulations did not consider neither the CO<sub>2</sub> fertilization effect nor the returns of dung and urine, which we believe were the main factors explaining the productivity increases that we predicted. Toreti et al. (2020) suggested that the recent efforts to estimate CO<sub>2</sub>-induced crop responses narrowed their uncertainties and make

mandatory to consider the CO<sub>2</sub> effect in climate change impact simulations. Kothari et al. (2022), from a multi-model study involving ten prominent models, analyzed separately the responses of soybean to temperature and CO<sub>2</sub> concentration increases, and reported for a one-year Brazilian location decreases of soybean yield under +3 °C temperature ranging from 38 % to no effect, and increases of 5 % to 41 % under a CO<sub>2</sub> concentration from 360 to 540 ppm. Tubiello et al. (2007) similarly reported increases of above-ground production in C3 pastures grasses and legumes from +10 to +20 %, under a CO<sub>2</sub> concentration of 550 ppm.

Moderate grazing was found to lead to the greatest augmentations in total herbage production and live weight gain when facing the climate change scenario. Grazing allows to benefit the most from the CO<sub>2</sub>-fertilization effect since the biomass growth restarts faster after each bite (simulated by a cut), whereas in the ungrazed treatment, sward biomass still reaches a plateau, yet earlier than in the historical climatic conditions.

It also appeared that the resistance capacities of herbage production and live weight gain to climatic events were greater under moderate grazing, in accordance with Modernel et al. (2019) which found greater resistance of herbage accumulation and animal live weight to droughts with moderate sheep grazing intensity compared to the overgrazing management typical in Uruguay.

Light to moderate grazing (G30 and G40) also proved to be ideal to increase carbon sequestration, in accordance with the literature (Sousana et al., 2010; Abdalla et al., 2018; Chang et al., 2021). The greater increase in SOC for the 2041–2058 period compared to the historical 2001–2018 one is due to the increase in biomass production combined with the increase in organic amendments that represent animals' dung and urine. That explains why the ungrazed treatment led to the smallest increase in SOC evolution. Moderate grazing was also found to store carbon deeper, which proved to be positive for organic carbon stability with lower turnover and mineralization rates, making it unlikely to respond rapidly to warming global temperatures and thus beneficial for soils fertility and climate change mitigation (Schumpf et al., 2013;

Soussana and Lemaire, 2014; Jackson et al., 2017). Since SOC depth distribution is closely related to roots depth distribution (Schrumpf et al., 2013), this also suggests that the greater resistance capacities of moderate grazing to extreme climatic events might originate from deeper rooting systems.

These results highlight the importance of crop-pastures rotations to increase the climate change mitigation potential that represent agricultural soils. Moreover, they suggest that, whenever it is possible, it would be profitable to increase the stocking rate to enhance the productivity and carbon sequestration, but only in the limits of the sward carrying capacity since our simulations showed that overgrazing leads to relatively smaller SOC stocks but also poorer adaptation to climate change. As explained by Soussana and Lemaire (2014), a tradeoff must be found between maximizing C harvest by grazing for live weight gain and maximizing C returned to the soil, which appears to be around sward heights of 30–40 cm under the considered pedoclimatic conditions and in association with no-till soybean.

#### 4.4. Assessing the potential of ICLS under climate change through process-based models

In Brazil, between 2010 and 2016, the Low Carbon Agriculture Plan successfully increased the number of ICLS at a rate of 1 million hectares per year (Rodrigues et al., 2019). Yet, the Brazilian example still constitutes an exception which was only made possible, as summarized by Moraes et al. (2014), by taking the most of the synergisms that result from no-till, a high plant functional diversity and *rotatinuous* stocking management (i.e. low intensity and frequent grazing (Carvalho, 2013)). The main challenges that brake ICLS wider adoption in other regions of the world include their high infrastructure, labor and financial capital requirements (and hence lack of investment), sustainable awareness and lack of skills by the farmers (Sekaran et al., 2021).

Overcoming these challenges requires new approaches to help lift the lock-ins, to which process-based models can bring answers. Process-based models allow to compare in silico various soil and plant management itineraries as well as different sequences of crop-pasture rotations, and constitute therefore naturally key tools to investigate the performance and behavior of contrasted ICLS. Allowing to experiment contrasted pedological and climatic (historical and future) conditions, they might become essential to investigate how ICLS can contribute for adapting to and mitigating climate change. So far, process-based models which simulate the interactions of crops, grasslands and animals at the level of the agroecosystem are still very rare. Our methodology, which might be generalized to any other process-based model able to simulate sward mowing and organic matter inputs, proved to be adequate to approximate and simulate ICLS with contrasted grazing intensities. We believe that an ever-better understanding of the role ICLS can play in guaranteeing a large, diversified and stable production will help to respond to the challenges preventing their wider adoption.

#### CRedit authorship contribution statement

**Mathieu Delandmeter:** Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Paulo César de Faccio Carvalho:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Carolina Bremm:** Data curation, Methodology. **Carolina dos Santos Cargnelli:** Data curation. **Jérôme Bindelle:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Benjamin Dumont:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

#### Data availability

Data will be made available on request.

#### Acknowledgement

This study was partially funded by the F.R.S.-FNRS (Belgian Fund for Scientific Research; Research Fellow grant (number 44221) awarded to M. Delandmeter), and by a CONFAP-WBI cooperation project (*Wallonie-Bruxelles International* - SUB/2022/564785, WBI, Brussels). We thank Amélie Gaudin for providing the weather data under future climatic conditions used in Peterson et al. (2020). We also thank Julie Constantin for sharing its parameterization of soybean with the STICS model, used in Kothari et al. (2022). We are also thankful to Loïc Strullu, Anne-Isabelle Graux and Fabien Ferchaud who shared the parameterization of pea and pasture plant files. We finally greet the entire team of the Research Group on Grazing Ecology (GPEP) of the UFRGS for hosting M. Delandmeter within their office and the sharing of their expertise on subtropical integrated crop-livestock systems.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2023.169061>.

#### References

- Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agric. Ecosyst. Environ.* 253, 62–81.
- Aguinaga, A.A.Q., Carvalho, P.C.D.F., Anghinoni, I., Santos, D.T.D., Freitas, F.K.D., Lopes, M.T., 2006. Produção de novilhos superprecosos em pastagem de aveia e azevém submetida a diferentes alturas de manejo. *Revista Brasileira de Zootecnia* 35, 1765–1773. <https://doi.org/10.1590/S1516-35982006000600026>.
- Alsajri, F.A., Wijewardana, C., Irby, J.T., Bellaloui, N., Krutz, L.J., Golden, B., Reddy, K.R., 2020. Developing functional relationships between temperature and soybean yield and seed quality. *Agron. J.* 112 (1), 194–204. <https://doi.org/10.1002/agj2.20034>.
- Asseng, S., Martre, P., Maiorano, A., Rötter, R.P., O’Leary, G.J., Fitzgerald, G.J., Ewert, F., 2019. Climate change impact and adaptation for wheat protein. *Glob. Chang. Biol.* 25 (1), 155–173. <https://doi.org/10.1111/gcb.14481>.
- Basu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J.W., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors? *Glob. Chang. Biol.* 20 (7), 2301–2320. <https://doi.org/10.1111/gcb.12520>.
- Beaudoin, N., Launay, M., Sauboua, E., Ponsardin, G., Mary, B., 2008. Evaluation of the soil-crop model STICS over 8 years against the “on farm” database of Bruyères catchment. *Eur. J. Agron.* 29 (1), 46–57. <https://doi.org/10.1016/j.eja.2008.03.001>.
- Beaudoin, N., Lecharpentier, P., Ripoché, D., Strullu, L., Mary, B., Leonard, J., Launay, M., Justes, E. (Eds.), 2022. STICS Soil-Crop Model. *Conceptual Framework, Equations and Uses*. Éditions Quae, Versailles.
- Bell, L.W., Moore, A.D., 2012. Integrated crop–livestock systems in Australian agriculture: trends, drivers and implications. *Agric. Syst.* 111, 1–12. <https://doi.org/10.1016/j.agys.2012.04.003>.
- Bell, L.W., Moore, A.D., Kirkegaard, J.A., 2014. Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. *Eur. J. Agron.* 57, 10–20. <https://doi.org/10.1016/j.eja.2013.04.007>.
- Bernabucci, U., 2019. Climate change: impact on livestock and how can we adapt. *Anim. Front.* 9 (1), 3–5. <https://doi.org/10.1093/af/vfy039>.
- Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. *Eur. J. Agron.* 57, 43–51. <https://doi.org/10.1016/j.eja.2013.09.010>.
- Boote, K.J., Prasad, V., Allen Jr., L.H., Singh, P., Jones, J.W., 2018. Modeling sensitivity of grain yield to elevated temperature in the DSSAT crop models for peanut, soybean, dry bean, chickpea, sorghum, and millet. *Eur. J. Agron.* 100, 99–109. <https://doi.org/10.1016/j.eja.2017.09.002>.
- Brisson, N., Launay, M., Mary, B., Beaudoin, N., 2009. *Conceptual Basis, Formalizations and Parameterization of the STICS Crop Model*, 297. Ed. Quae.
- Carvalho, P.C.F., 2013. Harry Stobbs memorial lecture: can grazing behavior support innovations in grassland management? *Trop. Grassl.-Forrajes Trop.* 1 (2), 137–155. [https://doi.org/10.17138/tgft\(1\)137-155](https://doi.org/10.17138/tgft(1)137-155).
- Cecagno, D., Gomes, M.V., Costa, S.E.V.G.D.A., Martins, A.P., Denardin, L.G.D.O., Bayer, C., Carvalho, P.C.D.F., 2018. Soil organic carbon in an integrated crop–livestock system under different grazing intensities. *Rev. Bras. Cienc. Agrar.* 13 (3), e5553, 7 p. <https://doi.org/10.5039/agraria.v13i3a5553>.
- Chang, J., Ciais, P., Gasser, T., Smith, P., Herrero, M., Havlík, P., Zhu, D., 2021. Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. *Nat. Commun.* 12 (1), 118.
- Clivot, H., Mouny, J.C., Duparque, A., Dinh, J.L., Denoroy, P., Houot, S., Mary, B., 2019. Modeling soil organic carbon evolution in long-term arable experiments with AMG model. *Environ. Model. Softw.* 118, 99–113. <https://doi.org/10.1016/j.envsoft.2019.04.004>.

- de Albuquerque Nunes, P.A., Laca, E.A., de Faccio Carvalho, P.C., Li, M., de Souza Filho, W., Robinson Kunrath, T., Gaudin, A., 2021. Livestock integration into soybean systems improves long-term system stability and profits without compromising crop yields. *Sci. Rep.* 11 (1), 1649. <https://doi.org/10.1038/s41598-021-81270-z>.
- de Moraes, A., de Faccio Carvalho, P.C., Anghinoni, I., Lustosa, S.B.C., de Andrade, S.E.V.G., Kunrath, T.R., 2014. Integrated crop–livestock systems in the Brazilian subtropics. *Eur. J. Agron.* 57, 4–9. <https://doi.org/10.1016/j.eja.2013.10.004>.
- de Souza, de Sousa, Sampaio, L.S., 2013. Soybean development and thermal requirement under the climatic conditions of Paragominas, Pará state, Brazil. *Revista de Ciências Agrárias/Amazonian Journal of Agricultural and Environmental Sciences* 56 (4), 371–375.
- de Souza Filho, W., de Albuquerque Nunes, Barro, R.S., Kunrath, T.R., de Almeida, Genro, T.C.M., et al., 2019. Mitigation of enteric methane emissions through pasture management in integrated crop–livestock systems: Trade-offs between animal performance and environmental impacts. *J. Clean. Prod.* 213, 968–975. <https://doi.org/10.1016/j.jclepro.2018.12.245>.
- Di Falco, S., Chavas, J.P., 2008. Rainfall shocks, resilience, and the effects of crop biodiversity on agroecosystem productivity. *Land Econ.* 84 (1), 83–96. <https://doi.org/10.3368/le.84.1.83>.
- Diles, J.J.B., Green, R.D., Shepard, H.H., Mathews, G.L., Hughes, L.J., Miller, M.F., 1996. Relationships between body measurements obtained on yearling brangus bulls and measures of carcass merit obtained from their steer clone-mates. *Prof. Anim. Sci.* 12 (4), 244–249. [https://doi.org/10.15232/S1080-7446\(15\)32530-4](https://doi.org/10.15232/S1080-7446(15)32530-4).
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Zaks, D.P., 2011. Solutions for a cultivated planet. *Nature* 478 (7369), 337–342. <https://doi.org/10.1038/nature10452>.
- Franzluebbers, A.J., 2010. Will we allow soil carbon to feed our needs? *Carbon Manag.* 1 (2), 237–251. <https://doi.org/10.4155/cmt.10.25>.
- Franzluebbers, A.J., Stuedemann, J.A., 2008. Early response of soil organic fractions to tillage and integrated crop–livestock production. *Soil Sci. Soc. Am. J.* 72 (3), 613–625. <https://doi.org/10.2136/sssaj2007.0121>.
- Franzluebbers, A.J., Sawchik, J., Taboada, M.A., 2014. Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. *Agric. Ecosyst. Environ.* 190, 18–26. <https://doi.org/10.1016/j.agee.2013.09.017>.
- Garrett, R.D., Ryschawy, J., Bell, L.W., Cortner, O., Ferreira, J., Garik, A.V., Valentim, J. F., 2020. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecol. Soc.* 25 (1), 24. <https://doi.org/10.5751/ES-11412-250124>.
- Gaudin, A.C., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One* 10 (2), e0113261. <https://doi.org/10.1371/journal.pone.0113261>.
- Graux, A.I., Resmond, R., Casellas, E., Delaby, L., Faverdin, P., Le Bas, C., Peyraud, J.L., 2020. High-resolution assessment of French grassland dry matter and nitrogen yields. *Eur. J. Agron.* 112, 125952. <https://doi.org/10.1016/j.eja.2019.125952>.
- Graux A.I., Cadéro A., Casellas E., Buis S., Charpentier P., Decau M.L., Louault F., Strullu L., Vertès F., Ferchaud F. (2023) Calibration and evaluation of the STICS model for long-term simulations of soil organic matter dynamics in grassland soils (in preparation).
- IPCC (2013). Summary for policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, 151 pp.
- IPCC (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. [P.R. Shukla, J. Sheea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
- Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop–livestock systems. *Science* 327 (5967), 822–825. <https://doi.org/10.1126/science.1183725>.
- IPCC, 2022. Summary for policymakers. In: Pörtner, H.-O., Roberts, D.C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Lösschke, S., Möller, V., Okem, A. (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Lösschke, V. Möller, A. Okem, B. Rama (eds.)]. In Press.
- Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Eisenhauer, N., 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526 (7574), 574–577. <https://doi.org/10.1038/nature15374>.
- Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G., 2017. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. *Annu. Rev. Ecol. Syst.* 48, 419–445. <https://doi.org/10.1146/annurev-ecolsys-112414-054234>.
- Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO<sub>2</sub> enrichment. *Adv. Agron.* 77, 293–368. [https://doi.org/10.1016/S0065-2113\(02\)77017-X](https://doi.org/10.1016/S0065-2113(02)77017-X).
- Klingman, D.L., Miles, S.R., Mott, G.O., 1943. The cage method for determining consumption and yield of pasture herbage. *J. American Soc. Agron.* 35, 739–746.
- Kothari, K., Battisti, R., Boote, K.J., Archontoulis, S.V., Confalone, A., Constantin, J., et al., 2022. Are soybean models ready for climate change food impact assessments? *European J. Agron.* 135, 126482. <https://doi.org/10.1016/j.eja.2022.126482>.
- Kunrath, T.R., de Albuquerque Nunes, P.A., de Souza Filho, W., Cadenazzi, M., Bremm, C., Martins, A.P., de Faccio Carvalho, P.C., 2020. Sward height determines pasture production and animal performance in a long-term soybean–beef cattle integrated system. *Agric. Syst.* 177, 102716. <https://doi.org/10.1016/j.agsy.2019.102716>.
- Laca, E.A., Ungar, E.D., Seligman, N., Dement, M.W., 1992. Effects of sward height and bulk density on bite dimensions of cattle grazing homogeneous swards. *Grass Forage Sci.* 47 (1), 91–102. <https://doi.org/10.1111/j.1365-2494.1992.tb02251.x>.
- Lemaire, G., Ryschawy, J., de Faccio, P.C., 2016. Agricultural intensification and diversity for reconciling production and environment. In: *Food Production and Nature Conservation: Conflicts and Solutions*, p. 113.
- Leng, G., Hall, J., 2019. Crop yield sensitivity of global major agricultural countries to droughts and the projected changes in the future. *Sci. Total Environ.* 654, 811–821. <https://doi.org/10.1016/j.scitotenv.2018.10.434>.
- Liebig, M.A., Morgan, J.A., Reeder, J.D., Ellert, B.H., Gollany, H.T., Schuman, G.E., 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil Till. Res.* 83 (1), 25–52. <https://doi.org/10.1016/j.still.2005.02.008>.
- Liebig, M.A., Tanaka, D.L., Kronberg, S.L., Scholljegerdes, E.J., Karn, J.F., 2012. Integrated crops and livestock in central North Dakota, USA: Agroecosystem management to buffer soil change. *Renew. Agri. Food Sys.* 27 (2), 115–124. <https://doi.org/10.1017/S1742170511000172>.
- Lin, B.B., 2011. Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience* 61 (3), 183–193. <https://doi.org/10.1525/bio.2011.61.3.4>.
- Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. *Proc. Natl. Acad. Sci.* 107 (17), 8035–8040. <https://doi.org/10.1073/pnas.0913658107>.
- Maia, S.M., Ogle, S.M., Cerri, C.C., Cerri, C.E., 2010. Changes in soil organic carbon storage under different agricultural management systems in the Southwest Amazon Region of Brazil. *Soil Tillage Res.* 106 (2), 177–184. <https://doi.org/10.1016/j.still.2009.12.005>.
- Martin, G., Moraine, M., Ryschawy, J., Magne, M.A., Asai, M., Sarthou, J.P., et al., 2016. Crop–livestock integration beyond the farm level: a review. *Agron. Sustain. Develop.* 36 (3), 53. <https://doi.org/10.1007/s13593-016-0390-x>.
- Mazoyer, M., Roudart, L., 2002. *Histoire des agricultures du monde. Du néolithique à la crise contemporaine*. Éditions du Seuil.
- Modernel, P., Picasso, V., Do Carmo, M., Rossing, W.A., Corbeels, M., Soca, P., Titttonell, P., 2019. Grazing management for more resilient mixed livestock farming systems on native grasslands of southern South America. *Grass Forage Sci.* 74 (4), 636–649. <https://doi.org/10.1111/gfs.12445>.
- Moraes, A.D., Carvalho, P.C.D.F., Lustosa, S.B.C., Lang, C.R., Deiss, L., 2014. Research on integrated crop–livestock systems in Brazil. *Rev. Ciênc. Agron.* 45, 1024–1031. <https://doi.org/10.1590/S1806-66902014000500018>.
- Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Mooney, H., 2005. Losing the links between livestock and land. *Science* 310 (5754), 1621–1622. <https://doi.org/10.1126/science.11178>.
- Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. Math. Phys. Eng. Sci.* 193, 120–145. <https://doi.org/10.1098/rspa.1948.0037>.
- Peterson, C.A., Nunes, P.A.D.A., Martins, A.P., Bergamaschi, H., Anghinoni, I., Carvalho, P.C.D.F., Gaudin, A.C., 2019. Winter grazing does not affect soybean yield despite lower soil water content in a subtropical crop–livestock system. *Agron. Sustain. Dev.* 39, 1–10. <https://doi.org/10.1007/s13593-019-0573-3>.
- Peterson, C.A., Bell, L.W., Carvalho, P.C.D.F., Gaudin, A.C., 2020. Resilience of an integrated crop–livestock system to climate change: a simulation analysis of cover crop grazing in southern Brazil. *Front. Sustain. Food Syst.* 4, 604099. <https://doi.org/10.3389/fsufs.2020.604099>.
- Peyraud, J.L., Peeters, A., 2016. The role of grassland based production system in the protein security. In: *Grassland Science in Europe – The Multiple Roles of Grassland in the European Bioeconomy*, 21, pp. 29–43.
- Poggio, L., De Sousa, L.M., Batjes, N.H., Heuvelink, G., Kempen, B., Ribeiro, E., Rossiter, D., 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil* 7 (1), 217–240. <https://doi.org/10.5194/soil-7-217-2021>.
- Poudel, S., Vennam, R.R., Shrestha, A., Reddy, K.R., Wijewardane, N.K., Reddy, K.N., Bheemanahalli, R., 2023. Resilience of soybean cultivars to drought stress during flowering and early-seed setting stages. *Sci. Rep.* 13 (1), 1277. <https://doi.org/10.1038/s41598-023-28354-0>.
- Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philos. Trans. R. Soc. B* 365 (1554), 2959–2971. <https://doi.org/10.1098/rstb.2010.0143>.
- Rai, T., Kumar, S., Nleya, T., Hoogenboom, G., 2022. Simulating the impact of crop–livestock interaction on crop performance using DSSAT. *Agrosystems Geosci. Environ.* 5 (4), e20303. <https://doi.org/10.1002/agg2.20303>.
- Rodrigues, R.D.A.R., Conceição, M.C.G., Bidone, E.D., Matos, E.S., Cordeiro, R.C., Selva, G.V., 2019. The actions of the Brazilian agricultural sector in the context of climate change negotiations. *Sustain.* Debate 10 (2), 28–37.

- Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering integrated crop–livestock systems in North America. *Agron. J.* 99 (2), 325–334. <https://doi.org/10.2134/agronj2006.0139>.
- Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I., Schulze, E.D., 2013. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. *Biogeosciences* 10 (3), 1675–1691. <https://doi.org/10.5194/bg-10-1675-2013>.
- Sejian, V., Bhatta, R., Gaughan, J.B., Dunshea, F.R., Lacetera, N., 2018. Adaptation of animals to heat stress. *Animal* 12 (s2), s431–s444. <https://doi.org/10.1017/S1751731118001945>.
- Sekaran, U., Lai, L., Ussiri, D.A., Kumar, S., Clay, S., 2021. Role of integrated crop–livestock systems in improving agriculture production and addressing food security—a review. *J. Agric. Food Res.* 5, 100190 <https://doi.org/10.1016/j.jafr.2021.100190>.
- Sionit, N., Kramer, P.J., 1977. Effect of water stress during different stages of growth of soybean 1. *Agron. J.* 69 (2), 274–278. <https://doi.org/10.2134/agronj1977.00021962006900020018x>.
- Smith, W., Grant, B., Qi, Z., He, W., Qian, B., Jing, Q., Wagner-Riddle, C., 2020. Towards an improved methodology for modelling climate change impacts on cropping systems in cool climates. *Sci. Total Environ.* 728, 138845 <https://doi.org/10.1016/j.scitotenv.2020.138845>.
- Soil Survey Staff, 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. USDA Natural Resources Conservation Service.
- Soussana, J.F., Lemaire, G., 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop–livestock systems. *Agric. Ecosyst. Environ.* 190, 9–17. <https://doi.org/10.1016/j.agee.2013.10.012>.
- Soussana, J.F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays, D., 2004. Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use Manag.* 20 (2), 219–230. <https://doi.org/10.1111/j.1475-2743.2004.tb00362.x>.
- Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* 4 (3), 334–350.
- Szabó, B., Weynants, M., Weber, T.K., 2021. Updated European hydraulic pedotransfer functions with communicated uncertainties in the predicted variables (eupfv2). *Geosci. Model Dev.* 14 (1), 151–175. <https://doi.org/10.5194/gmd-14-151-2021>.
- Thornton, P.K., Herrero, M., 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nat. Clim. Chang.* 5 (9), 830–836. <https://doi.org/10.1038/nclimate2754>.
- Toreti, A., Deryng, D., Tubiello, F.N., Müller, C., Kimball, B.A., Moser, G., Rosenzweig, C., 2020. Narrowing uncertainties in the effects of elevated CO<sub>2</sub> on crops. *Nature Food* 1 (12), 775–782.
- Tracy, B.F., Zhang, Y., 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop–livestock system in Illinois. *Crop Sci.* 48 (3), 1211–1218. <https://doi.org/10.2135/cropsci2007.07.0390>.
- Tubiello, F.N., Soussana, J.F., Howden, S.M., 2007. Crop and pasture response to climate change. *Proc. Natl. Acad. Sci.* 104 (50), 19686–19690. <https://doi.org/10.1073/pnas.0701728104>.
- USDA, 2019. USDA National Nutrient Database for Standard Reference. Retrieved from <https://fdc.nal.usda.gov/index.html>.
- Verhoeven, J.T., Arheimer, B., Yin, C., Hefting, M.M., 2006. Regional and global concerns over wetlands and water quality. *Trends Ecol. Evol.* 21 (2), 96–103. <https://doi.org/10.1016/j.tree.2005.11.015>.
- Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J. Clim.* 23 (7), 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>.
- Wen, J., Zhao, X.X., Chang, C.P., 2021. The impact of extreme events on energy price risk. *Energy Econ.* 99, 105308 <https://doi.org/10.1016/j.eneco.2021.105308>.
- Zanon, A.J., Streck, N.A., Grassini, P., 2016. Climate and management factors influence soybean yield potential in a subtropical environment. *Agron. J.* 108 (4), 1447–1454. <https://doi.org/10.2134/agronj2015.0535>.