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Strategies for future robust meat production and climate change mitigation under imported input constraints in Alentejo, Portugal

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1 Abstract

The Alentejo region in Portugal is vital to the country's beef industry and home to 60% of the Portuguese beef cattle population. Farmers increasingly rely on imported synthetic fertilizer and feed. The uncertainty of global oil supply, and indirectly inputs, calls into question the robustness of the beef farming system in Alentejo, defined as the capacity of the system to sustain its function (beef production) in spite of a disturbance (decreased input availability). An additional challenge is the need for reducing greenhouse gas emissions to meet decarbonization goals. At present, these challenges are being addressed through management practices such as expanding areas of high-yield sown biodiverse pastures and fattening steers partially on grass rather than concentrates. These practices have shown to reduce greenhouse gas emissions, but their effect on the robustness of beef production when inputs are scarce is unknown. To fill this gap, we adapted a dynamic nitrogen mass flow model to assess herd dynamics and calculate a greenhouse gas emissions balance. We applied the model for seven scenarios corresponding to different combinations of management practices over fifty years with increasing input constraints. We estimated, without changes and without constraints, a greenhouse gas balance of 55 kgCO$_2$-e kg carcass^{-1} year^{-1} (100-years global warming potential). Without changes but faced with constraints, meat production dropped 60% (low long-term robustness) in 50 years while increasing by 17% the greenhouse gas balance. Our results show that a combination of high-yield legume-rich pastures, maximization of grass intake, herd size reduction, and increased animal productivity allowed the smallest reduction of meat production (28%) and largest greenhouse gas emission reduction (30%, i.e., 38.9 kgCO$_2$-e kg carcass^{-1} year^{-1}). Of the combinations studied, it was the best at mitigating the trade-off between robust meat production and climate change mitigation.

2 Keywords

Beef cattle farming systems; Dynamic model; Nitrogen mass flow balance; Sown biodiverse pastures rich in legumes; Peak oil

3 Introduction

In southern European Mediterranean regions, grassland-based beef cattle farming systems (BCFS) are an important part of the rural economy (Araújo et al. 2014). However, as droughts become longer and more frequent, crop yields have been decreasing, threatening feed self-sufficiency (Nardone et al. 2010; Jongen et al. 2013; Scasta et al. 2015; Huguenin et al. 2017; Karimi et al. 2018), and farmers have been relying more on imported forages and feed concentrates, as well as synthetic fertilizers for pasture improvement (Rodrigues et al. 2020). If, as suggested, global peak oil is near (IEA 2018; Delannoy et al. 2021), increased oil prices could threaten the supply of these imported agricultural inputs that support BCFS. The resulting economic instability and social disruption might also jeopardize the robustness of meat markets (Anderson 2009; Weis 2013), specifically, the ability of BCFS to maintain their meat supply despite disturbances.

In the Portuguese region of Alentejo, grass-based BCFS are part of *Montado* ecosystems. These ecosystems are extensive dry woodland, in which low-density forests co-exist with grassland understory, the latter often grazed by sheep and cattle (Figure 1) (Pereira et al. 2009). The agricultural sector, including beef production, is economically important in Alentejo, representing more than 11% of the total gross value added (Instituto Nacional de Estatistica 2020). Alentejo is the main beef production region in Portugal (more than 45% of the cattle population in Portugal is in Alentejo – Instituto Nacional de Estatistica (2020)), exporting within Portugal and to other European and Middle Eastern countries (Araújo et al. 2014). However, it is also among the most desert regions in Europe and vulnerable to any decline in imported agricultural inputs arising from oil price increases. Additionally, BCFS in Alentejo contributes approximately 30% of the greenhouse gas (GHG) emissions of the Portuguese agricultural sector, mainly from enteric fermentation (APA 2018). The Portuguese government has set the reduction of CH_4 emissions from enteric fermentation as a policy goal, aiming to decrease the beef cattle population by 25% by 2050, while increasing the productivity of beef cattle to compensate for the decreased meat production caused by the reduction of the number of heads (Republica Portuguesa 2019). Therefore, BCFS in Alentejo face the double challenge of ensuring robustness of their meat supply to mitigate the effects of increased energy costs while reducing GHG emissions. Following Meuwissen et al. (2019), by robustness we mean the capacity of a farming system to deliver its functions in spite of a disturbance, without changing its configuration (definition also coherent with Anderies et al. (2002); Accatino et al. (2014); Pinsard et al. (2021)).

Figure 1. "Alentejana beef cattle grazing in a Montado ecosystem in Alentejo, Portugal" by João H.N. Palma. No changes

were made to the picture. CC BY-NC-ND 2.0

Two promising management practices have been partially adopted by Alentejo farmers seeking to reduce GHG emissions. They can also contribute to climate change adaptation and to improving BFCS economic viability. These practices are: (a) shifting low-yield semi-natural pastures to sown biodiverse pastures rich in legumes (Morais et al. 2018; Teixeira et al. 2018b), and (b) finishing steers on grass rather than on energy and protein concentrates (Costa et al. 2012). Sown biodiverse pastures, mixes of up to 20 different high-yield grasses and legume seeds are more productive than natural pastures (Teixeira et al. 2011; Valada et al. 2012; Proença et al. 2015; Moreno et al. 2021). Finishing animals on grass reduces the cost of feeding and improves animal health and welfare (Hocquette et al. 2014) but can also increase CH_4 emissions from enteric fermentation due to the lower digestibility of grass (IPCC 2019a). The two practices are sometimes implemented jointly, but trade-offs may occur between meat production and climate change mitigation A dynamic modeling approach would be useful to study the robustness of meat production to increasing prices of fossil-fuel intensive inputs while reaching GHG emission reduction targets for Alentejo BCFS.

Here, we modeled the impact of management practices and combinations thereof on the robustness of beef production and GHG emissions of the BCFS in Alentejo facing constraints on imported inputs. At the farming system level, we analyzed the trade-off between minimizing GHG emissions and increasing the robustness to declines in imported input availability. We adapted the dynamic biophysical model of Pinsard et al. (2021) by adding a sub-model of herd dynamics and meat production and a sub-model to account for GHG emissions. In the following, we first describe the model and the scenarios considered. Then, we compare and identify combinations of management practices that enhance robustness of meat production. Finally, we calculate the GHG balance of the different combinations of management practices, asking whether scenarios that enhance robustness can also meet GHG reduction targets set by the Portuguese government.

4 Materials and methods

4.1 Model overview

We added beef cattle herd dynamics and a GHG balance sub-model to the N-flow dynamic one-year time step model by Pinsard et al. (2021). The BCFS is divided into two land uses (composed of a soil and a plant compartment): permanent pastures and cropland (Figure 2). Soil compartments are composed of an active organic matter stock and a mineral nitrogen flow, plant compartments are composed of surfaces occupied by different crop or permanent pasture types. The BCFS is also composed of a beef cattle herd compartment composed of age and sex groups (hereafter cohorts) with different dietary requirements (adapted from Puillet et al. (2014)). Cattle's manure is distributed between housing (and applied over cropland), and pastures. Body weight gain is a sigmoidal function with an annual time step and distinct between males and females.

Nitrogen flows through compartments in mineral and organic forms. Carbon flows only in organic form based on nitrogen through C:N ratios (except soil organic carbon). Imported feed and synthetic fertilizer are external inputs. Plant yields depend on the soil mineral nitrogen available after losses (for legumes, it is also affected by biological nitrogen fixation). Variation in head number was a function of feed shortage, calculated comparing the requirements with available (imported and locally produced) feed. Nitrogen losses occurred during soil and manure management.

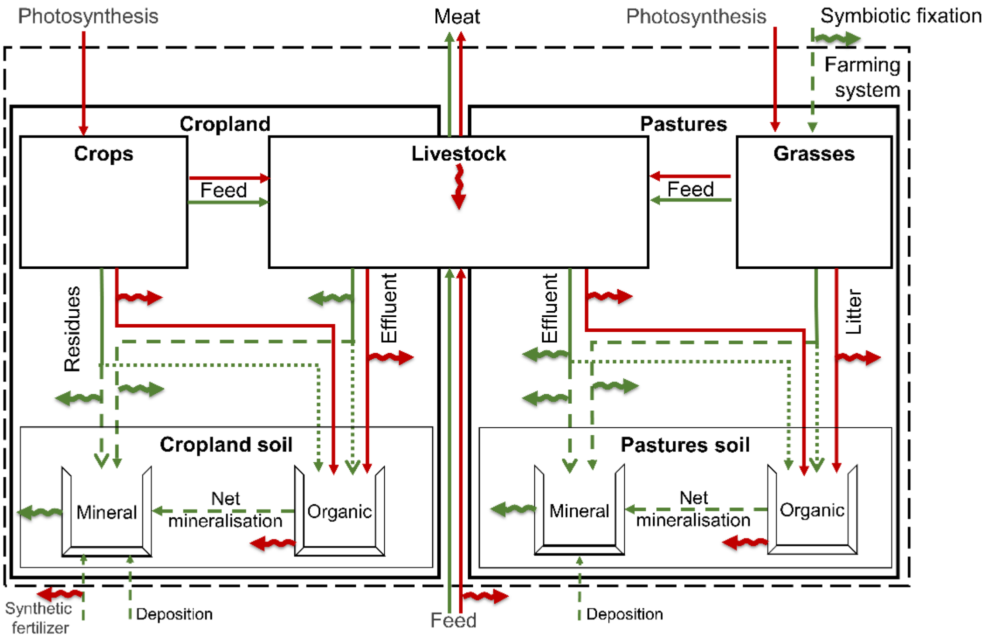

Figure 2. Conceptual scheme of the model. Boxes represent compartments and arrows are the nitrogen (in green) or carbon flows (in red). Nitrogen flows are: mineral (dashed lines), organic (point lines), or mixed (full lines). The wavy arrows represent gaseous or liquid nitrogen or carbon losses.

4.2 Model description

We briefly describe the main model equations in the following sections (a complete description is in the Supplementary Material file). Variables refer to nitrogen (letter n) or carbon (letter c).

4.2.1 Plant

Each crop or pasture type i has a set of traits (assumed constant) useful for calculating biomass production (following Clivot et al. (2019)): area, typical yield of harvested/grazed organ y^{TYP}[kg fresh matter ha^{-1} year^{-1}], harvest index, consumption index (the part effectively grazed) for pastures, shoot-to-root ratio, nitrogen and carbon contents of the different parts of the plant, humification coefficients for the plant residues, the nitrogen quantity fixed by legumes per hectare and the share of digestible energy for beef of the edible part. We assumed that yield $y_{i,t}$ [kg fresh matter ha^{-1} year^{-1}] increases linearly from 0 to the typical yield and then it saturates: $y_{i,t} = \max\left(y_i^{TYP}, \dot{n}_{i,l,t}^{Fert,Av} * \frac{y_i^{TYP}}{\dot{n}_{i,l}^{TYP}}\right)$, where $\dot{n}_{i,l,t}^{Fert,Av}$ is the soil mineral nitrogen available and $\dot{n}_{i,l}^{TYP}$ the soil mineral nitrogen needed by a plant to reach the typical yield (both in kgN ha^{-1} year^{-1}). Nitrogen surplus is lost to the environment. Crop residues from croplands can be used as feed in the barn, if allocated to the livestock rather than buried in the soil.

4.2.2 Soil

The variables characterizing the soil compartment for each land use l are the active organic nitrogen stock , the active organic carbon stock $c_{l,t}^{Soil}$ [kgC ha^{-1} year^{-1}] and the flow of mineral nitrogen. Organic amendments (crop residues and solid manure) are applied homogeneously the year after. Mineral nitrogen is either consumed by plants or lost at each time step. A part of organic amendments humifies. For carbon, the non-humified part goes to the atmosphere as CO_2. For nitrogen, if the share of the organic amendment that humifies is higher than its nitrogen content, the difference is subtracted from the soil organic nitrogen mineralization, i.e., is immobilized. On the contrary, the mineral share of the organic amendment is available to plants.

Soil organic carbon and nitrogen dynamics

The dynamics of soil organic carbon are a mass balance equation (Clivot et al. 2019):

$$c_{l,t+1}^{Soil} = c_{l,t}^{Soil} * (1 - \mu_l) + \dot{c}_{l,t}^{rA} + \dot{c}_{l,t}^{rR} + \dot{c}_{l,t}^{E} \ . \tag{1}$$

Input terms are the humified carbon of amendments per hectare (*i.e.*, the aboveground plant residues $\dot{c}_{l,t}^{rA}$, belowground plant residues $\dot{c}_{l,t}^{rR}$ and cattle manure $\dot{c}_{l,t}^{E}$ (in kgC ha^{-1} year^{-1})). The output term is the mineralization of soil organic carbon (being μ_l [-] the mineralization rate).

We derived the dynamics of soil organic nitrogen from equation (1) by multiplying by C:N ratios and accounting for immobilization (Supplementary Material).

Mineral nitrogen flows and losses

The soil mineral nitrogen available for plants includes the atmospheric deposition, the mineral part of organic amendments, synthetic mineral fertilizer (for crops), and the biological nitrogen fixation (for legumes crops).

Application of nitrogen to the soil leads to losses as N_2O (denitrification and nitrification), NH_3 (volatilization) and NO_3^- (leaching) that we assessed following a Tier 2 approach using default emission factors from IPCC (2019) or local emission factors from APA (2018) and Aguilera et al. (2021). Direct N_2O emissions and leaching occur for all the mineral nitrogen flows applied on cropland or on pastures (soil management). Volatilization happens during application of organic amendments and synthetic fertilizer. Indirect N_2O emissions occur during volatilization and leaching.

4.2.3 Beef cattle herd

The herd was divided into five cohorts based on age (a = 1, < 1 year old; a = 2, 1 – 2 years old; a = 3,> 2 years old) and sex (s = M for males, s = F for females): young steers $(1, M)$, old steers $(2, M)$, young heifers $(1, F)$, old heifers $(2, F)$, suckler cows $(3, F)$. The quantity of meat produced (in kg carcass) is a function of the number of heads slaughtered, and their live weight at the beginning of the year or at the end of the year for old steers. We assumed that the carcass weight of the Alentejo cattle breeds is approximately 60% of the live weight. Herd dynamics are detailed in Figure 3 and the equations are available as Supplementary Material.

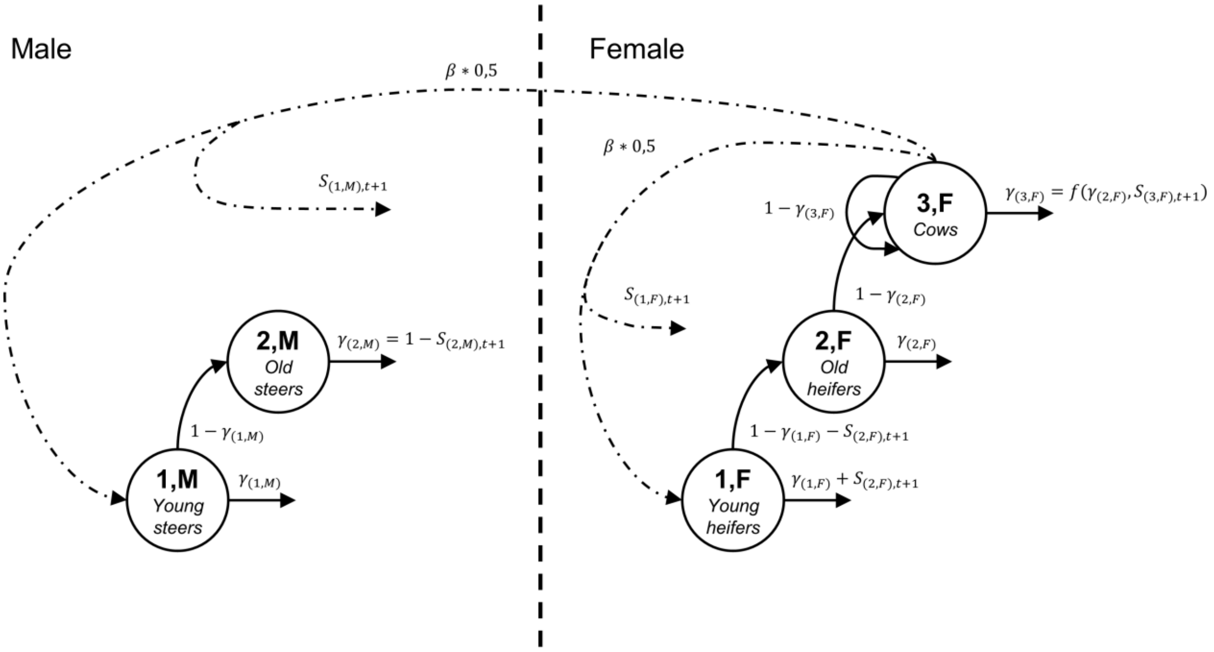

Figure 3 Beef cattle herd dynamics by age and sex cohorts. Cows (3,F) give birth to young steers (1,M) and young heifers (1,F). Continuous arrows leaving the circles correspond to fractions of animals slaughtered (γ) or going to the next age cohort ($1-\gamma$). These shares depend on feed shortage coefficients $S_{(a,s),t}$. Point-dot arrows leaving cows (3,F) correspond to the birth of offspring. A share β of the cows (3,F) give birth, with a ratio of female to male calves of 50%. Feed shortage can lead to the premature slaughter of offspring, young heifers (1,F), and cows (3,F), and to final weight decrease for old steers (2,M).

Each cattle cohort may have several diets (different compositions of feed categories) during the year. From this, it is possible to compute feed requirements for each feed category.

The shortage coefficient $S_{(a,s),k,t}$ [-] per cattle cohort (a, s) and per feed category k is equal to the difference between the feed requirement $\dot{N}^{Feed,Req}_{(a,s),k,t}$ [kgN year^{-1}] and the feed available $\dot{N}^{Feed,Av}_{(a,s),k,t}$ [kgN year^{-1}] and it is null in case $\dot{N}^{Feed,Req}_{(a,s),k,t} \leq \dot{N}^{Feed,Av}_{(a,s),k,t}$.

Empirical evidence from Alentejo suggests that, in the event of a shortage, cows are fed first to maintain the level of Common Agricultural Policy subsidies, which depend on the number of cows ("suckler cow premium") (Viegas et al. 2012). However, incorporating this practice in the model led during feed shortages to inter-annual variations or sharp decrease in herd size and consequently in meat production. As these variations would not be realistic in case of feed shortages, we chose a feed priority order that avoid it: heifers are first fed (old and then young), then the suckler cows and finally the steers (young and then old).

The quantity of cattle manure per cohort is computed as the difference between the feed intake and the nitrogen accumulation in the animals, and (for cows) the nitrogen in offspring, and milk. Excreta are allocated to housing facilities or permanent pastures proportionally to the time spent in the two places.

Excreta generated in housing facilities are stored before being applied to crops the following year. The storage of cattle manure result in direct emissions of N_2O, NH_3, and losses of NO_3^-. Volatilization and leaching lead to indirect emissions of N_2O. We followed a Tier 2 approach using default emission factors from IPCC (2019).

4.2.4 GHG balance

The GHG sub-model estimates (following Teixeira et al. (2018)) the emissions of the three main greenhouse gases (CO_2, CH_4, and N_2O; Ritchie and Roser 2020) and develops GHG balance at the BCFS level. Photosynthetic carbon capture during plant growth was obtained following Clivot et al. (2019). We multiplied the carbon content of the different parts of the plant by the crop yield, the harvest index, and the shoot-to-root ratio for plant residues. We considered the carbon content of imported feed in the GHG balance.

CO_2 emission flows

CO_2 emissions from soil organic carbon mineralization were obtained by multiplying the active soil organic carbon stock $c^{Soil}_{l,t}$ by the mineralization rate μ_l (see equation (1)). CO_2 emissions from the mineralization of organic amendments correspond to the total carbon quantity of the amendment deducted from the carbon quantity humified. We considered CO_2 emissions embedded in the imported synthetic fertilizer and feed, due to transportation and production. For synthetic fertilizer, we used an emission factor for Western Europe (in kgCO$_2$ kgN^{-1}) (FAO 2017). For feed import, we considered CO_2 emissions linked to production as well as transportation by truck. For production, we used an emission factor (in kgCO$_2$ kg^{-1}) that considered the feed type and the localization of the production of the imported feed for the beef cattle in Alentejo (Morais et al. 2018). For transportation, we multiplied the biomass weight by an emission factor (in kgCO$_2$ (ton.km)$^{-1}$) (ADEME 2012) accounting for an average distance of 1000 km (roundtrip distance between the north of Portugal, source of most imported feed compounds, and the Alentejo region), and a carbon content of 50% of the biomass imported (TNO Biobased and Circular Technologies 2021).

We assessed CO_2 emissions of cattle respiration as the difference between carbon intakes (feed), the quantity accumulated in body tissues, and out-takes (enteric fermentation, excretion, offspring, and milk). The carbon quantities of feed intake and excretion were obtained by multiplying their nitrogen quantities by their respective C:N ratios. Accumulation of feed intake as body weight gain per cattle cohort corresponds to the number of heads multiplied by the variation in live weight and the carbon content of body tissues (considering 65% body water content). The carbon in offspring was obtained, considering the initial live weight as 0.

Non-CO_2 emission flows

Methane emissions from cattle manure were calculated using an emission factor for the total quantity of carbon and deducted from the manure carbon to estimate mineralization-related CO_2. Methane emissions from enteric fermentation were computed using the Tier 2 IPCC (2019) equation for non-dairy cattle with the CH_4 yield, linearly interpolated along feed digestibility. Feed digestibility is the sum of the digestible energy per crop consumed by beef cattle herd per feed category, divided by the total gross energy for the feed category considered. We used, for the digestibility per crop, INRAE feed nutritional values for ruminants (Nozière et al. 2018).

Total GHG balance

The annual total GHG balance is the sum of all the GHG flows for one year from both land use and from the cattle herd, converted into CO_2-e using the global warming potential for 100 years (GWP_{100}) or the global warming potential star (GWP*) for CH_4. The CO_2 flows captured by plants during photosynthesis are negative values. The use of GWP* for short-lived gases in the atmosphere (approximately 20 years for CH_4) is recommended as it is particularly relevant when assessing their impact on global average temperature over time, or in the case of a net zero-GHG-emissions target (IPCC 2021 - Box 7.3). Indeed, the GWP* allows approximation of the impact of short-lived gases emissions on the climate more accurately than GWP_{100}, while the use of GWP_{100} underestimates the impact on the climate when emissions increase exponentially and overestimates it when they are constant or decreasing (Lynch et al. 2020; Thompson and Rowntree 2020). We decided to calculate the GHG balance with both coefficients, to compare the carbon intensity of meat production with other studies, which use the GWP_{100} coefficient. We considered the global warming potentials from the fifth assessment report of the IPCC without carbon feedbacks (Myhre et al. 2013).

4.2.5 Parameters and state variables

We collected data for 2018. For cropland, permanent pastures, and cattle herd parameters, we used the values from Teixeira et al. (2018) and Pinsard et al. (2021). Details regarding sources are available in Supplementary Material. The model was coded in R language using the package "deSolve" for solving the dynamic equation system (Soetaert et al. 2021).

Head numbers of suckler cows came from the statistical database of Instituto Nacional de Estatistica (2020).

Head numbers for other cattle cohorts were computed with the cattle population dynamics equations, considering no feed shortage. We applied an average set of parameters to the beef cattle herd. The live weight at birth and of one-year steers were based on the average growth curve (of steers) of the breeds Alentejana, Angus, Charolais and Limousine. The live weights of 2-years heifers, 18-months steers and 3-years suckler cows came from the slaughter carcass weights in Alentejo in 2020 from Instituto Nacional de Estatistica (2020) database. The live weight of one-year heifers was obtained by performing a sigmoidal regression of the average growth curve (of steers) of the breeds Alentejana, Angus, Charolais and Limousine setting a maximum value equal to the average slaughter weight of 3-years suckler cows.

The total quantities of above- and belowground residues are initialized using typical values of plant yield in Alentejo (average value over several years in different farms). For both land uses, soil organic carbon stock in the 10 cm soil depth was set equal to the average measured organic carbon content multiplied by the average measured bulk density (12 000 kgC ha^{-1} for cropland and 11 600 kgC ha^{-1} for permanent pastures) (Ballabio et al. 2016). We used soil organic nitrogen stocks using a C:N ratio equal to 30 for permanent pastures (Teixeira et al. 2018a) and 10 for cropland (Clivot et al. 2019). For both land uses, we estimated the mineralization rate equal to 13% using the equation of the version 2 of the AMG model (Clivot et al. 2019), and assumed about 35% of active soil organic matter stocks in the 10 cm soil depth. We then initialized the active soil organic matter stock in the 10 cm soil depth using the spin-up method (Xia et al. 2012), and considering the immobilization phenomenon for the nitrogen cycle.

4.3 Simulations

4.3.1 Management practices

We considered three management practices widely diffused in Alentejo: (i) increasing sown biodiverse pastures (Pasture Productivity, "*PP*"), (ii) shifting from a concentrate-based diet to a forage-based diet for old steers (Fattening on Forage, "*FF*"), and (iii) increasing animal productivity while decreasing herd size to reach the GHG target fixed by the Portuguese government (Livestock Decrease, "*LD*") (Republica Portuguesa 2019).

The practice "*PP*", is intended to increase productivity. This should make the farms more self-sufficient in fodder while reducing net GHG emissions, as increased biomass production increases carbon sequestration, but also depending on the stocking rate (Abdalla et al. 2018) and the time since sowing (Morais et al. 2018). In 2014, there were 140 000 hectares of sown biodiverse pastures in Portugal (4% of its agricultural land (Teixeira et al. 2015)), and we assumed that this has not changed much. The practice "*FF*" involves fattening old steers on permanent pastures to reduce input cost and increase farm self-sufficiency. We considered that old steers are full-time kept in housing facilities while other cohorts graze year-round. The practice "*LD*" is intended to decrease GHG to meet the goals set by the Portuguese government of reducing for instance CH_4 emissions from enteric fermentation by 25% from 2020 to 2050 (Republica Portuguesa 2019). The directive suggests "changes in the numbers of the various species" and "productivity improvements through genetics", which may involve reducing head number, genetically improving animal productivity in the cases where it is possible, and shifting to more productive breeds to maintain the meat production levels.

4.3.2 Simulated scenarios

Scenarios were combinations of a challenge and three practices, simulated over a 50-year horizon (until 2070). The challenge consisted of reduced external inputs (synthetic fertilizers and feed imports). In the simulation, the imposed trajectory started from an initial value and decreased linearly to 0 after 30 years (in 2050). The remaining 20 years of simulation display the inertia effects. The initial value of the availability of imported synthetic fertilizer corresponds to the total initial nitrogen crop needs. The initial value for the availability of imported feed in each feed category corresponds to the initial feed requirements per feed category.

We assumed that practices were put in place with linear increase. Practice "*PP*" was modeled by doubling of the initial sown biodiverse pasture area share over the semi-natural pasture area by 2050. Practice "*FF*" corresponded to a shift to a diet composed of 70% of forages. Practice "*LD*" was modeled as a 25% decrease in head number of suckler cows and a 10% increase in animal productivity, assumed to be achieved by the replacement of crossbreeds by the most productive breeds (Charolais and Limousine) (IFAP 2020; Marques et al. 2020). Although these management practice changes would be made at the farm level, we modeled their cumulative effect at the scale of the farming system.

We simulated seven scenarios (see Table 1). The first scenario is the *status quo* with no challenge (*SQ-NC*) or changes in management practices, serving as a baseline against which to assess the effect of the other scenarios on the robustness of meat production and net GHG emissions. There were six other scenarios: without management practices, so to assess the effect of the challenge (*EC*); with increased pastures productivity (*PP*); with diet shift of old steers to a forage-based diet (*FF*); with head number decrease and animal productivity increase (*LD*); with combinations of "*PP*" and "*FF*" (*PP-FF*); and with the three practices together (*PP-FF-LD*).

Scenario	Feed and synthetic fertiliser: Import availability decrease	Permanent pastures: Increase in sown biodiverse pasture area share (*PP*)	Fattened old steers: Shift from a concentrate-based diet to a forage-based diet (FF)	Animal productivity increase and herd size decrease (*LD*)
Baseline (*SQ-NC*)				
Effect of the challenge (*EC*)	V			

Increase of permanent pasture productivity (*PP*)	V	V		
Steers finished on permanent pastures (*FF*)	V		V	
GHG Roadmap 2050 (*LD)*	V			V
Increase of permanent pasture productivity and steers finished on permanent pastures (*PP-FF)*	V	V	V	
GHG Roadmap 2050 with increase in feed self-sufficiency (*PP-FF-LD)*	V	V	V	V

Table 1 Challenge and management practices (columns) combination per scenario (rows). The "V" indicates that the challenge or management practice change for the column in question is present in the scenario for the line in question. (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease).

5 Results and Discussion

5.1 Initial feed self-sufficiency

From the input data, we estimated the initial feed self-sufficiency as the nitrogen ratio of feed requirements over local feed availability per feed category. At time 0, old steers only ate concentrates and were the only cohort fed on concentrates. The concentrate requirements of steers older than one year were about 4 250 tons of nitrogen per year (for 94 500 steers) (Figure 4). Local concentrate ingredients were mostly barley and wheat and satisfied more than 65% of the concentrate requirements. The forage requirements of the other beef cattle cohorts were about 33 000 tons of nitrogen per year, mostly consumed by cows and heifers older than one year. Young heifers and steers are weaning suckler cows half of the year. Local forage production came primarily from permanent pastures and fulfilled more than 88% of forage requirements.

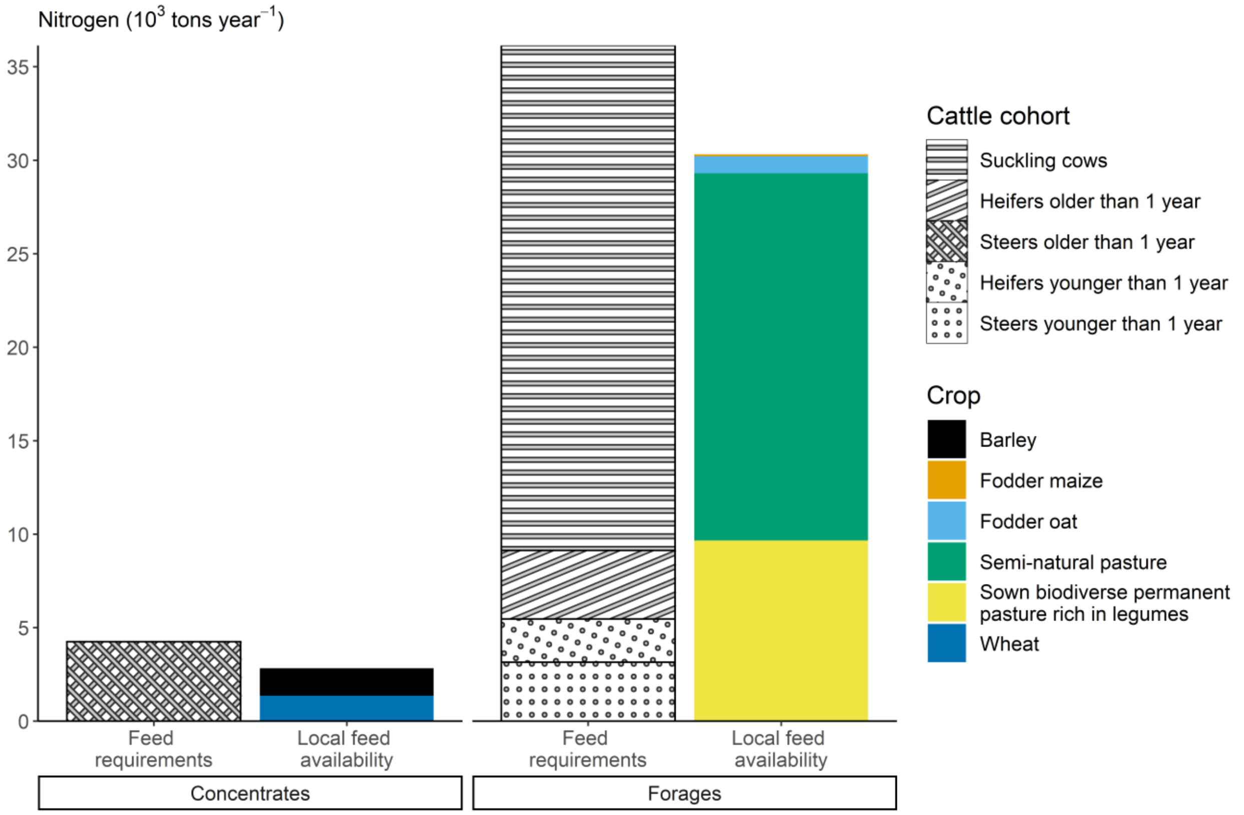

Figure 4. Feed requirements versus local feed availability of the beef cattle farming systems in Alentejo per feed category (horizontal facets) in tons of nitrogen per year. On the x-axis, the stacked bars on the left represent the feed requirements per cattle cohort, and the stacked bars on the right represent the local feed availability per crop. For a feed category, the local feed availability divided by feed requirements corresponds to the local feed self-sufficiency of that feed category. Feed self-sufficiency for both feed categories ranged from 65% to almost 90%. Beef cattle largely graze semi-natural or sown biodiverse pastures in Alentejo. Local feed availability from sunflower and soybean were not represented because it was negligible.

Local feed production and the diet of the different cattle cohorts suggested that the BCFS was almost fodder self-sufficient. This estimate agrees with the survey conducted by Santos et al. (2019), in which 70% of beef farmers in Alentejo reported being self-sufficient in fodder. Considering a 90% fodder self-sufficiency of the BCFS in Alentejo, the 30% non-self-sufficient beef farms have thus a forage self-sufficiency of about 70%. In contrast, the BCFS was not self-sufficient in concentrates, in line with agricultural statistics. However, the estimated concentrates self-sufficiency in the BCFS in Alentejo is higher than the national concentrates self-sufficiency in 2020 (less than 20%) (Instituto Nacional de Estatistica 2020).

5.2 Temporal dynamics of meat production

The time trajectories of meat production varied across the different scenarios (Figure 5). Without a voluntary decrease in the number of heads (all scenarios except *LD* and *PP-FF-LD*), the trajectories of meat production overlapped for the first 20 years and were constant over time at more than 60 000 tons carcass. Regardless of the combination of practices considered, meat production decreased over the 50 years when imports decreased, with an uncertainty interval that increased during the simulation and could go up to -35% and +45% due to uncertainties on biomass production and stocking rate (see Supplementary Material). However, some trajectories were more robust than others. Either meat production began to decline later in the simulation (short-term robustness), or the decline was less at the end of the simulation (long-term robustness).

Both short- and long-term, the *PP-FF* trajectory was the most robust and the *EC* and *LD* trajectories were the least robust. In the *PP-FF* scenario, meat production only decreased from year 25 onwards, to approximately 48 000 tons after 50 years. As Alentejo is home to more than 60% of Portuguese beef cattle (IFAP 2020), we assume that more than 60% of its beef production is also. With this assumption, the level of production would decline to levels of the early 1970s in the *PP-FF* scenario (Instituto Nacional de Estatistica 2020). In the *LD* scenario, the meat production decreased from the beginning of the simulation and overlapped with *PP-FF-LD* scenario until year 18. At the end of the simulation, 26 000 tons of carcass had been produced. In the *PP-FF-LD* scenario, meat production was 45 000 tons in year 50. This was the second most robust scenario in the long term, just a bit less robust than the *PP-FF* scenario. In the *EC* and *PP* scenarios, production started to decline in year 17, while in *PP-FF* scenario, it started in year 25. The production declined in the *FF* scenario in year 27, before the decline in *PP-FF* scenario, with a production peak of 67 000 tons of carcass in year 24. This peak of production, that we could also see in scenario *EC* and *FF*, was due to a fodder shortage increasing the culling rate, the slaughter of young steers having not been sufficient (see Figure 2 in the Supplementary Material). We observed a decline in production with increased forage self-sufficiency (scenarios *PP, PP-FF, PP-FF-LD*), and suggest that the productivity of local crops is high and import of synthetic fertilizers is necessary to maintain crop yields and, indirectly, meat production. Interestingly, we found that the decrease in meat production after 30 years in the *EC* scenario is similar (more than 40%) to that of animal production in the Bocage Bourbonnais (an extensive ruminant farming system whose main production is also beef) in a similar scenario (Pinsard et al. 2021). However, the Alentejo is more robust in the short term than the Bocage Bourbonnais for a nitrogen productivity twice as low (Jouven et al. 2018).

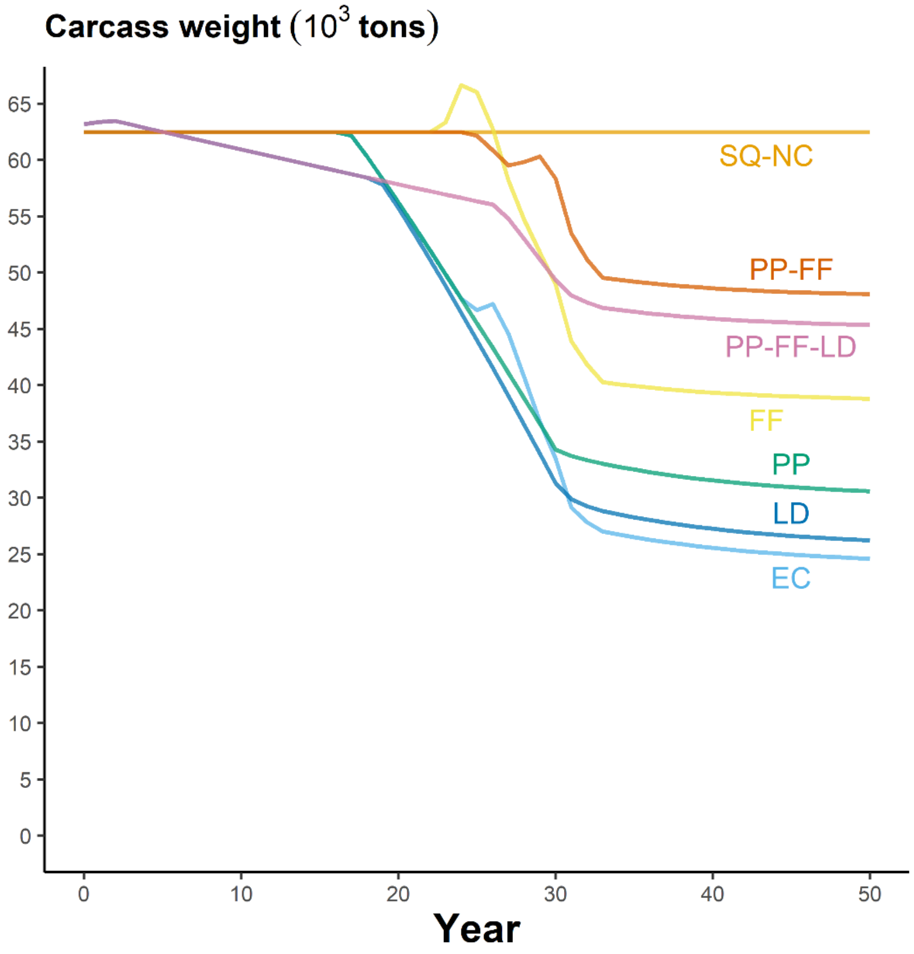

Figure 5. Meat production in the different scenarios over 50 years as predicted by the model. The SQ-NC scenario is the baseline scenario; the status quo with no challenge or change in management practices. In the EC scenario, the challenge is implemented with no management practice. In the PP scenario permanent pastures productivity was increased. In the FF scenario, the diet of old steers was shifted from a concentrate-based diet to a forage-based diet. In the LD scenario, animal productivity was increased, and head number decreased as part of the roadmap of the Portuguese government to reduce greenhouse gas emissions. In the PP-FF and PP-FF-LD scenarios, both management practices were implemented. (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease). The results of the global sensitivity analysis are available in Supplementary Material.

The *PP* scenario resulted in greater self-sufficiency with respect to forage, but less self-sufficiency with respect to concentrates. The latter was due to decreased local crop production resulting from a shortage of synthetic fertilizer. We observed the opposite in the *FF* scenario: there was less need for concentrates and greater need for forage. The *PP* trajectory was less robust, in the short and long term, than the *FF* trajectory, and we concluded that shortage of concentrates was more detrimental to production than shortage of forage, perhaps because only the old steers consumed concentrates. Also, since old steers are intended for meat production, a decrease in their feed will result in reduced live weight at slaughter.

5.3 GHG emissions

5.3.1 Per emission flow

Nitrous oxide emissions from soil management was the largest N_2O flow over the 50 years (~70 $kgCO_2$-e ha^{-1} $year^{-1}$) (Figure 6a). The N_2O emission flow from manure management accounted for about 20 $kgCO_2$-e ha^{-1} $year^{-1}$ (Figure 6b). Enteric fermentation was the largest CH_4 emission flow (~580 $kgCO_2$-e ha^{-1} $year^{-1}$ with the GWP* and ~2 330 $kgCO_2$-e ha^{-1} $year^{-1}$ with the GWP_{100}) (Figure 6c). The CH_4 emission flow from manure on management accounted for about 60 $kgCO_2$-e ha^{-1} $year^{-1}$ with the GWP*, and about 240 $kgCO_2$-e ha^{-1} $year^{-1}$ with the GWP_{100} (Figure 6d).

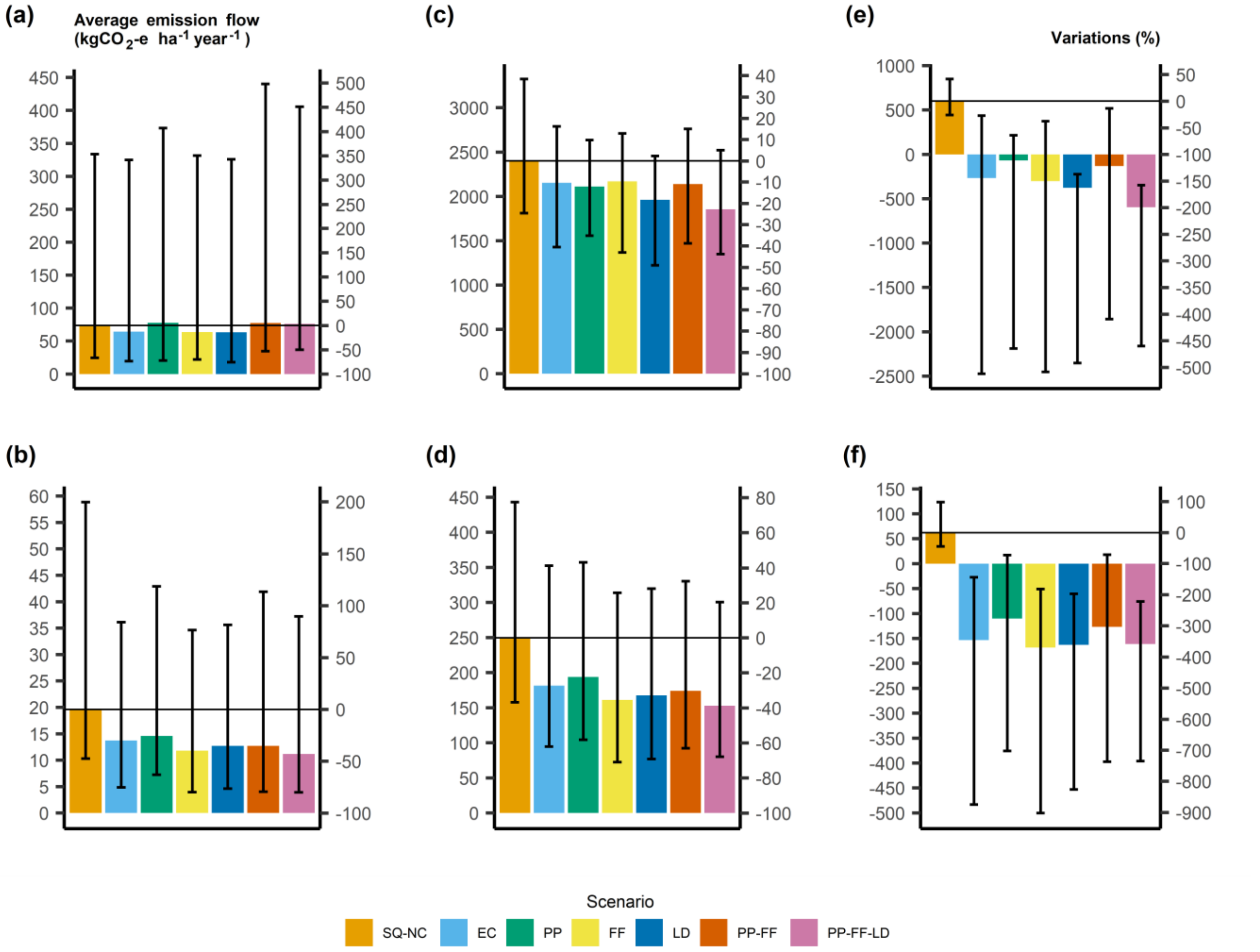

Figure 6. Annual average greenhouse gas (GHG) emission flows for the different scenarios for the 50-year simulation time. (a) N_2O emissions from soil management (b) N_2O emission flow from manure management (c) CH_4 emission flow from enteric fermentation with the GWP^{100} metric (global warming potential over 100 years) (d) CH_4 emission flow from manure management with the GWP^{100} metric (e) CH_4 emission flow from enteric fermentation with the GWP^* (short-term global warming potential) metric (f) CH_4 emission flow from manure management with the GWP^* metric. The right axis shows emission variations in % from the baseline scenario (SQ-NC). (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock

decrease). The error bars represent the minimum and maximum values of a global sensitivity analysis (100 iterations - parameter value ranges are in Supplementary Material).

In case of increased pasture productivity (*PP*, *PP-FF* and *PP-FF-LD* scenarios), the 50-year annual average N_2O emission flows from soil management was slightly higher than in the baseline scenario (*SQ-NC*) (by 5%) (Figure 6a). The increase in N_2O emissions from soil management was related to the shift to sown biodiverse pastures, which led to an increase in mineral nitrogen flow in the permanent pastures soil (Teixeira et al. 2018a). In all the scenarios with the challenge, the 50-year annual average N_2O emissions from manure management were between 25% and 45% less than in the baseline scenario (*SQ-NC*) (Figure 6b). This decrease is a proxy for the decrease in the number of livestock or the decrease in feed consumption by old steers due to the lack of available feed (see Supplementary Material – section “Results”).

In all the scenarios with the challenge, the 50-year annual average CH_4 emissions from enteric fermentation were lower than in the baseline scenario (*SQ-NC*) (Figure 6c). Methane emission flow from enteric fermentation was the highest in the *PP* and *PP-FF* scenarios among all the scenarios with the challenge, when considering both GWP_{100} and GWP* metrics. This is due to a robustness of the livestock number both on the short-term and on the long-term (see Supplementary Material – section “Results”) and to a diet with more fiber, source of lower digestibility (Beauchemin et al. 2008; de Vries et al. 2015; Nozière et al. 2018; McAuliffe et al. 2018). The CH_4 emission flow from enteric fermentation was the lowest in scenarios *LD* and *PP-FF-LD* when considering both GWP_{100} and GWP* metrics. The CH_4 emission flow from enteric fermentation was lower in the *PP-FF-LD* scenario compared to the *LD* scenario due to a slightly higher digestibility of sown biodiverse pastures compared to semi-natural permanent pastures. The global sensitivity analysis showed that the uncertainty range was the highest for that emission flow (± 500 $kgCO_2$-e ha^{-1} $year^{-1}$ with GWP_{100} and down to -2 500 $kgCO_2$-e ha^{-1} $year^{-1}$ with GWP*) as livestock number reduction can be important with lower feed self-sufficiency. The annual average CH_4 emissions over the 50-year simulation from manure management were always lower than those in the baseline scenario (*SQ-NC*) (between 20% and 40% with GWP_{100}) (Figure 6d). The lower the head number after 50 years, the lower this emission flow with the GWP* (see Supplementary Material – section “Results”).

5.3.2 Total balance

In the baseline scenario in total, the 50-year annual average CO_2 balance, considering only CO_2 flows, was approximately 420 $kgCO_2$-e $head^{-1}$ $year^{-1}$ (Figure 7a). The 50-year annual average total non-CO_2 GHG balance was approximately 1 300 $kgCO_2$-e $head^{-1}$ $year^{-1}$ with the GWP* and 4 800 $kgCO_2$-e $head^{-1}$ $year^{-1}$ with the GWP_{100} (Figure 7b).

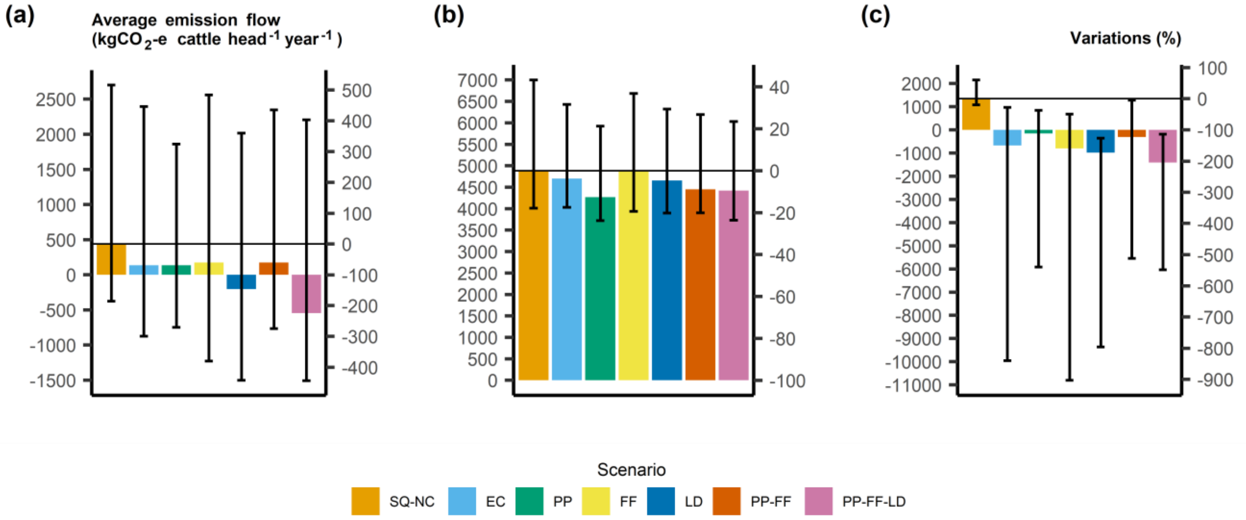

Figure 7. Annual average greenhouse gas (GHG) balances for the different scenarios for the 50-year simulation time. (a) Total CO_2 balance. (b) Total non-CO_2 GHG balance with the global warming potential over 100 year (GWP^{100}) metric (c) Total non-CO_2 GHG balance with the short-term global warming potential (GWP^*) metric. Total CO_2 balance is the sum of CO_2 emission flows. The total non-CO_2 GHG balance is the sum of N_2O and CH_4 emission flows. The right axis shows emission variations in % from the baseline scenario (SQ-NC). (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease). The error bars represent the minimum and maximum values of a global sensitivity analysis (100 iterations - parameter value ranges are in Supplementary Material).

Total CO_2 balance in all scenarios was lower than in the baseline scenario and negative in scenarios with reduced head number (*LD* and *PP-FF-LD* scenarios) (Figure 7a). However, the uncertainty range is wide in all the scenario (up to 2 500 kgCO_2-e head^{-1} year^{-1}) due to uncertainties on the emission factors of the imported feed and synthetic fertilizer. In scenario *PP*, in which pasture productivity increased, the total CO_2 balance decreased by about 70%, despite a constant number of grazing livestock (see Supplementary Material – section “Results”), due to an increase in soil carbon stocks in grasslands (Teixeira et al. 2018a) and a decrease in fodder imports. The balance was slightly higher in *FF* and *PP-FF* scenarios than in the *PP* scenario, although the soil organic carbon stocks increase is similar, because the feed import, which is source of net CO_2 emissions, is higher.

Total non-CO_2 GHG balance was lower (or equal) in all scenarios than in the baseline scenario, with both GWP metrics (Figure 7b). The decrease of head number coupled to animal productivity increase (*LD* and *PP-FF-LD* scenarios) reduced total non-CO_2 GHG balance the most, more than 200% from the baseline scenario with GWP*. This result is explained because a decrease in herd size coupled with an increase in individual productivity will inevitably reduce CH_4 from enteric fermentation without increasing N_2O emissions (Herrero et al. 2013; Ripple et al. 2014).

5.4 Total GHG balance versus meat production robustness

There was a strong trade-off between total GHG balance and robustness of meat production that varied with simulation time. Some efficiency gains were possible, depending on the combination of management practices changes put in place. However, maintaining meat production prevented strong reductions of GHG emissions (with the GWP_{100} metric), and GHG emission reductions established in policy objectives were only possible with reductions of meat production.

In scenarios without reduction in head number (*EC, PP, FF,* and *PP-FF* scenarios), with the GWP_{100}, the annual average total GHG balance (in $kgCO_2$-e kg carcass^{-1} year^{-1}) was higher than or slightly lower to the baseline scenario (between +17% and -8%), while with the GWP* it was lower than the baseline scenario (between -3% and -40%) (Figure 8). In *LD* and *PP-FF-LD* scenarios, with the GWP_{100}, the annual average total GHG balance was equal or lower than the baseline scenario, down to -30%, while with the GWP*, the decrease reached about -110%. The global sensitivity analysis showed values down to -800% with GWP* with a parameter set giving a low feed self-sufficiency (e.g., lower forage digestibility, lower biomass production, lower stocking rate – see Supplementary Material) and a high livestock number reduction (and thus a lower meat production).

The annual average total GHG balance per unit of meat produced was about 55 $kgCO_2$-e kg carcass^{-1} year^{-1} with the GWP_{100} in the baseline scenario (between 45 and 80 $kgCO_2$-e kg carcass^{-1} year^{-1} in the uncertainty range), in line with the median value of GHG balances of beef production (all types of beef production systems) collected by Poore and Nemecek (2018), assuming 25% protein in beef meat and a carcass to fat and bone-free-meat yield of 70% (52.5 $kgCO_2$-e kg carcass^{-1} year^{-1} – mean equal to 87.5 $kgCO_2$-e kg carcass^{-1} year^{-1}). However, this estimate is much higher than past estimates for this farming system in Portugal or for similar farming systems in Spain, Europe, Brazil, USA or Thailand where the estimates (in $kgCO_2$-e kg carcass^{-1} year^{-1} – we assumed a live-weight to carcass yield of 60%) are respectively 37.7 (Teixeira et al. 2018a), 29.6, 33.3 (Eldesouky et al. 2018; Reyes-Palomo et al. 2022), 21-28 (Weiss and Leip 2012), 37.5 (Dick et al. 2015), 32 (Pelletier et al. 2010), 23.3 (Ogino et al. 2016). This difference is mainly explained by the large methane flow from enteric fermentation estimated in this study (Tier 2 approach) due to the low digestibility of the grazed grass and the fact that the main feed intake is forages (except for steers in some scenarios). Regarding the latter, unsurprisingly it represents the largest GHG flow in all scenarios. It amounted more than 90% of the non-CO_2 GHGs in the baseline scenario as in Reyes-Palomo et al. (2022) for a similar BCFS. However, this share is larger than in other GHG balances of this or similar farming systems (between 45% and 65%) (Eldesouky et al. 2018; Teixeira et al. 2018a) due to lower N_2O flows.

The annual average total GHG balance per unit of meat produced was less than 20 $kgCO_2$-e kg carcass^{-1} year^{-1} with the GWP* in the baseline scenario. The more than 2-fold difference between GWP_{100} and GWP* observed while CH_4 emissions are not changing in the baseline scenario, shows how much GWP_{100} leads to an overestimation of the impact of CH_4 emissions on the climate at constant or decreasing rate of emissions.

The annual average total GHG balance per unit of meat produced was lower than in the baseline scenario in all the scenarios when GWP* was considered (negative values), but not always when GWP_{100} was considered (Figure 8). In the scenarios without reduced animal numbers (*EC, PP, FF,* and *PP-FF* scenarios), the total GHG balance per unit of meat produced when GWP_{100} was used was higher or slightly lower than in the baseline scenario. In other words, the metric used determined whether we estimated an increase or decrease in net GHG emissions per unit of meat produced compared to the baseline.

Finally, both with GWP_{100} and GWP*, the total GHG balance per unit of meat produced was the lowest in the *LD* and *PP-FF-LD* scenarios (respectively -14.8 and -20 $kgCO_2$-e kg $carcass^{-1}$ $year^{-1}$ with the GWP* metric). This can be explained by the decrease in CH_4 emissions from enteric fermentation and manure management which had a positive (cooling) effect on the climate in these scenarios ("negative emissions" in CO_2-e), as the volume of CH_4 in the atmosphere associated with the BCFS decreased significantly (after 20 years the CH_4 emitted 20 years ago has been converted to CO_2). This phenomenon was captured with the GWP* metric but not with the GWP_{100} metric (see Supplementary Material – section "Results"). After a 30-year decrease, CH_4 emissions from enteric fermentation stabilized and the earlier positive effect on the climate decreased in the following 20 years to a new equilibrium with again a negative effect on climate. Thus, a longer time horizon for the simulations would lead to an increase in the total GHG balance with the GWP* metric without significantly impacting the total GHG balance with the GWP_{100} metric.

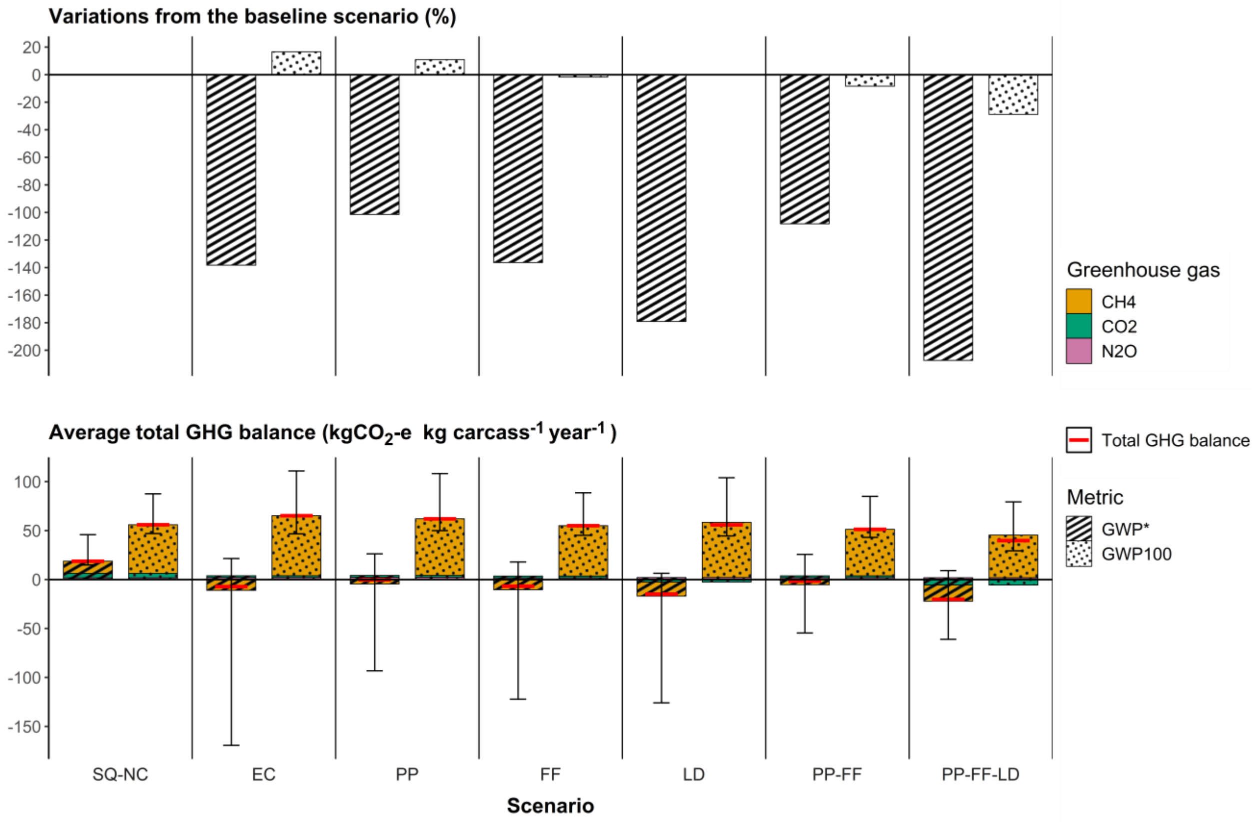

Figure 8. The annual average of the total greenhouse gas (GHG) emissions balance for the 50-year simulation, using GWP_{100} and the GWP per greenhouse gas. Upper panel, variations from the baseline scenario (SQ-NC) in %; Lower*

panel, in kgCO$_2$-e kg carcass^{-1} year^{-1}. (SQ-NC, status quo with *no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease; GWP$_{100}$, global warming potential over 100 years; GWP*, short-term global warming potential). The error bars represent the minimum and maximum values of a global sensitivity analysis (100 iterations - parameter value ranges are in Supplementary Material).*

Combining all the practices (*PP-FF-LD* scenario), was the best compromise between meat production robustness and climate change mitigation (with both metrics) over the next 50 years (Figure 5 and Figure 8). However, animal productivity gains targeted by the Portuguese government's roadmap were insufficient to maintain meat production (*LD* and *PP-FF-LD* scenarios) (Republica Portuguesa 2019). Increasing the productivity of permanent pastures (e.g., with sown biodiverse pastures) combined with a diet with more forages supported meat production the most and decreased net GHG emissions (Morais et al. 2018), as observed in the *PP-FF* scenario. However, this was not sufficient for the decarbonization of the sector (considering the GWP$_{100}$ metric), as in any of the scenarios. Indeed, the Portuguese government's roadmap projects a 50% reduction in emissions from agriculture, by decreasing losses of carbon in cropland soils and by increasing carbon sequestration in permanent pastures soils by 2050 compared to 2020 (Republica Portuguesa 2019). However, with the GWP* metric, a 50% reduction in net GHG emissions in this agricultural sub-sector was largely achieved in all the scenarios with the challenge. In this case, the *PP-FF* scenario allows for the best combination of climate change mitigation and robust meat production. However, in the long term (by the end of the century and beyond) it will be necessary to decrease the herd size based on the positive CO$_2$-e emissions associated with it (CH$_4$ and N$_2$O emissions) to maintain a net zero GHG balance for the Portuguese agricultural sector.

The significant differences in results according to the GWP metric used (results also depending on the time horizon) can thus lead to different or nuanced conclusions, notably according to the reduction target set (fixed or search for a maximum) and the scope (spatial and sectoral). In other words, on the one hand, the use of the GWP* metric in the context of a zero net emissions objective for the agricultural sector by 2050 could lead to a downward revision of the ambitions to reduce the cattle population by 2050. On the other hand, with national and global scale objectives of minimizing the rate of increase in average air temperatures in the short term, the use of the GWP* metric would lead to an upward revision in these ambitions.

5.5 Implications and limitations of implementing practice changes

We could not consider the possible effects of implementation of the three management practices at the level of the farm or farming system, for example on the work organization, the economy of the BCFS, and new imported flows in the BCFS. These may impose limits to the implementation of these practices, for example, changing management practices may affect the resilience of the farm and BCFS.

The sowing of biodiverse pastures requires machinery for tillage to prepare the field for sowing and fertilizing (Teixeira et al. 2011). During the process, phosphorus, borax, and zinc sulfate are applied as cover fertilization, lime is applied to increase the soil pH, and 30 kg ha^{-1} of seeds are used. The pastures should last for at least 10 years but may require frequent applications of phosphorus fertilizer and limestone during this time. Considering that energy supply and input prices may be uncertain in the future, the profitability of establishing and maintaining new sown biodiverse pastures may change. Assessing how would require a dedicated economic study of the system that exceeds the scope of this analysis.

Fattening old steers on grass takes at least 18 months, longer than it does on concentrates (Keane et al. 2006; Morales Gómez et al. 2021), due to lower nutritional value of grass compared to concentrates (Brosh et al. 2004; IPCC 2019a), and the increased energy expenditure of grazing animals (Brosh et al. 2004; IPCC 2019a). We assumed in our model that grass-fattening did not take longer than 24 months. Furthermore, in reality, this practice is limited in recent years, especially in Alentejo, by the increased frequency of droughts due to climate change and resultant decreased forage production (Nardone et al. 2010; Jongen et al. 2013; Scasta et al. 2015; Huguenin et al. 2017). Therefore, without increasing the resilience of permanent pastures to drought, specifically, without increasing sown biodiverse pasture area, the implementation of this practice could harm the robustness of the BCFS. Nevertheless, from an economic perspective, grass-fattening increases self-reliance of the farm and reduces costs (Escribano et al. 2016). The added value at sale may also be greater as it coincides with the preferences of Portuguese consumers (Marta-Pedroso 2008, Banovic 2009).

We assumed a 10% increase in animal productivity over 30 years, probably accomplished by transitioning the cattle population in Alentejo towards the most productive breeds (Charolais and Limousin) and away from the current indigenous Portuguese suckler breeds or the Angus breed (Schenkel et al. 2004; Santos-Silva et al. 2020). In 2020, however, only 16.3% of the Alentejo cattle population were indigenous Portuguese suckler breeds (pure or crossbreeds) or the Angus breed (IFAP 2020), and 61% were unspecified beef crossbreeds with unknown productivity. However, if the individual productivity of these crossbreeds is close to that of the pure indigenous breeds in Portugal, then an increase in individual productivity at herd level should be possible. Nevertheless, such a change in the composition of the cattle herd would run counter to the approach of preserving the genetic heritage of the indigenous suckler breeds (Araújo et al. 2014), and, even if less productive, native suckler breeds are adapted to the Mediterranean climate and recommended for extensive systems affected by harsh soil and climatic conditions. Although feasible, the productivity of ostensibly highly productive breeds is not apparent in such a climate and these breeds are more susceptible to diseases when changing diets in extensive BCFS (Pereira et al., 2008). Increasing animal productivity facing increasing drought may not only require consideration of herd composition, but also genetic selection of individuals within a pure breed or in the herd and decreasing cow size while increasing herd size (which could also increase methane emissions) (Nardone et al. 2010; Scasta et al. 2016).

According to this model, reduction in head number is unavoidable if we are to meet GHG reduction targets (from a GWP_{100} perspective). This is not explicitly mentioned in the Portuguese roadmap for carbon neutrality, which ideally requires measures to encourage and accept a reduction in the beef demand and financial incentives to help professional conversion of some economic stakeholders of the Alentejo BCFS. Moreover, the drop in beef demand would contribute to Portugal's self-sufficiency, *i.e.,* would help to reduce the trade deficit (target commonly mentioned in the government's political statements). In 2020, in Portugal, beef consumption amounted to an average of 20.8 kg inhabitant^{-1}, i.e., approximately 400 g per week (Instituto Nacional de Estatistica 2020). The beef production in Alentejo estimated with this model in 2020, with an assumption of 70% carcass/marketable meat yield, is then sufficient for 20% of this national consumption. In case of a meat consumption halving by 2070, in the worst-case scenario (*LD* and *EC* scenarios) beef production in Alentejo would be sufficient for 17% of Portuguese meat consumption, while in the best-case scenario (*PP-FF* scenario) it would be sufficient for 33%, a number similar to the 70s-80s (Instituto Nacional de Estatistica 2020). Despite the limitations, there are levers that could support the successful implementation of these management practices. Portuguese consumers are willing to pay more for meat if it is of better quality, thus making it possible to increase the selling price if the production cost increases (Banovic 2009). Meat from a grass-finished animal is darker, has a stronger taste, and healthier fatty acids; it is indeed preferred by well-informed consumers (Marta-Pedroso 2008). The area of sown biodiverse pastures in 2009-2014 was greatly expanded as a result of the financial and technical support of the Portuguese Carbon Fund (Teixeira et al. 2015). Similar schemes could be devised to encourage a decrease in herd size coupled with an increase in individual animal productivity, as well as to encourage farmers to finish steers on grass.

5.6 Study and model limitations

The main limitations of our work were the scope of the GHG balance, the resolution of the soil organic matter modeling, the method of active soil organic matter estimation, and the exclusion of other challenges facing an extensive BCFS.

For the GHG balance, we considered both emissions from production and transportation of imported feeds and synthetic nitrogen fertilizers. However, we excluded the emissions associated with import of seeds and production of phosphorus fertilizers for sown biodiverse pastures. We did not consider them for three main reasons: (i) they only concern the sowing of the pasture, (ii) we lacked data, (iii) we considered the amount negligible compared to the other emission flows (Teixeira et al. 2018).

In our adapted model, land use (cropland or permanent pastures) consists of only one soil type with a single organic matter pool, on which the application of organic amendments is homogeneous. This implies an overestimation or underestimation of the stock of organic matter in the soil and of the net mineralization flow available to plants at the plot level, which also leads to a mis-estimation of biomass production (specifically for sown biodiverse pastures). This choice was due to lack of data on soil amendments and cropping practices for the plots in the region, but it would be appropriate to compare the soil organic matter values for these two levels of model complexity.

Regarding carbon sequestration, we found very low values for permanent pastures’ soil in *PP* and *PP-FF* scenarios (600 kgC ha^{-1} over 50 years, *i.e.,* +0.07% of organic matter in the 10 cm soil depth (initial soil organic carbon matter of 1.5%)) compared to the +0.5% of organic matter expected (~7 tC ha^{-1}) from the measured and modeled soil organic matter content in Alentejo pastures (Teixeira et al. 2011) (near estimate in Pelletier et al. (2010) for an improved cow-calf pastures). This significant difference is mainly explained by the assumption of equilibrium at the beginning of the simulations (constant practices the 30 years before the beginning of the simulation) used to determine the stock of active soil organic carbon that led to its overestimation.

The challenges that the extensive BCFS in Alentejo may face include climate change, policy reforms, and global peak oil. All of these, for different reasons, could decrease local feed and meat production, and agricultural imports. Regarding climate change, the region is increasingly facing droughts and heat waves that decrease the biomass production and quality of permanent pastures (Jongen et al. 2013; Huguenin et al. 2017). Consequently, farmers must buy or import fodder and concentrates to secure their feeding system, making them dependent on external feed production and markets, and increasing the cost of production. Taking into account the impact of climate change on biomass production and quality, as well as on animal productivity and herd management, in the simulations, in addition to input supply constraints, would undoubtedly lead to a lower robustness of meat production in both the short and long term and higher GHG emissions (increased enteric fermentation). This decrease could be more important in the scenarios with grass-fed steers (*FF*, *PP-FF* and *PP-FF-LD*) than in the other scenarios, because of a greater shortage of fodder. However, the conclusions would most likely remain unchanged, i.e., the implementation of the combination of practices would still best reconciles climate change mitigation and robust meat production, despite the impact of climate change. Regarding policy reforms, the Common Agricultural Policy could continue to favor the intensification of extensive beef cattle farms (e.g., intensification of forage production, cropland irrigation), making them also more dependent on imported feed or synthetic fertilizers and on subsidies (Jones et al. 2014) but perhaps more robust to climate change impacts.

5.7 Future research perspectives

Climate change will undoubtedly have a major effect on the extensive BCFS in Alentejo. Simulating the farming sensitivity to possible future climate scenarios, by considering the impact of droughts on plant yield and quality, and heat wave on animal productivity and herd management, is a logical next step, and explicit modeling of farmers' economic responses to increasing prices of input prices and droughts should help identify policy mechanisms and incentives that would enhance robustness of meat production. Finally, phosphorus is a critical element for sown biodiverse pastures fertilization (Teixeira et al. 2011) and comes mainly from non-renewable rock reserves. The production peak of these fertilizers could occur at the same time as peak oil (Cordell and White 2011). Therefore, the phosphorus cycle should be added to the model to assess the impact of global peak oil and global peak phosphorus on meat production, pinpointing the management practices changes that enhance both meat production robustness and GHG emission reduction.

The main unique aspect of our study is the dynamic exploration of changes in Alentejo extensive BCFS. Our results showed that robustness of meat production to input import constraints and net GHG emissions are contrasting objectives that do not increase jointly in the scenarios explored. However, such trade-off can be softened depending on the combination of management practices changes put in place. In other words, enhancing only meat production robustness may compromise GHG emission reduction targets or vice versa, unless there is a major change in the way farmers manage their land and their farms.

To our knowledge, another unique aspect is the study of changes in a context of declining feed and synthetic fertilizer import (due to peak oil), exploring at the same time the effects on the animal production and the GHG balance. Some previous studies addressed either only the GHG balance (de Vries et al. 2015; Poore and Nemecek 2018) or only the meat production robustness of a BCFS to declines in imported agricultural inputs (Pinsard et al. 2021). As for previous studies that addressed both (animal production and GHG balance), constraints on inputs were not considered (Herrero et al. 2013; Puillet et al. 2014; Brandt et al. 2018; Teixeira et al. 2018a; Hawkins et al. 2021).

6 Conclusions

Two critical policy goals in agriculture are to enhance the robustness of meat production to respond to unpredictable supply and price variations of inputs and to reduce GHG emissions. Those two goals were little investigated jointly in previous studies. To fill this gap, we explored in Alentejo BCFS via modeling, whether management practices put in place to mitigate and/or adapt to climate change, alone and in combination, would address both goals. Our results showed that these latter can be potentially in conflict. They also showed that, combined, those management practices mitigated climate change even when the farms faced decreased supplies of synthetic fertilizer and imported feed, while individual practices were insufficient (considering GWP_{100} metric). However, in those cases meat production could not be maintained at the current levels. We found that an option for ensuring the robustness of meat production and maximizing the reduction of net GHG emissions is a combination of all management practices considered here. Nevertheless, herd decrease and individual animal productivity increase would need to be more ambitious for reducing net GHG emissions over the next 50 years to levels compatible with the GHG reduction roadmap of the Portuguese government. From a GWP* perspective, finishing old steers on grass while increasing the productivity of permanent pasture would be enough to promote robust meat production and reduce significantly net GHG emissions (and be compatible with the roadmap). Nevertheless, the pursuit of this net zero emission target for the agricultural sector will still imply, for a longer time horizon, a decrease in the size of the cattle herd.

7 Declarations

7.1 Funding (information that explains whether and by whom the research was supported)

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7.2 Conflicts of interest/Competing interests (include appropriate disclosures)

The authors have no conflicts of interest to declare that are relevant to the content of this article.

7.3 Ethics approval (include appropriate approvals or waivers)

Not applicable.

7.4 Consent to participate (include appropriate statements)

Not applicable.

7.5 Consent for publication (include appropriate statements)

Not applicable.

7.6 Availability of data and material (data transparency)

The formatted data used as input to the model as well as output data are available in Zenodo repository, https://doi.org/10.5281/zenodo.5727504. The raw input data is freely available from the sources mentioned in the Supplementary Material.

7.7 Code availability (software application or custom code)

The R code done to make the simulations of the current study is available in Zenodo repository, https://doi.org/10.5281/zenodo.5727504.

7.8 Authors' contributions (include appropriate statements)

All authors contributed to the study conception and design. C. Pinsard designed the model. The study was supervised by R. Teixeira and T. Domingos. Data collection was performed by T. Morais and C. Pinsard. Coding, simulating, and output visualization were done by C. Pinsard. All the authors validated model outputs. The first draft of the manuscript was written by C. Pinsard and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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