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

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13

14 1 Abstract

15 The Alentejo region in Portugal is vital to the country's beef industry and home to 60% of the Portuguese beef
16 cattle population. Farmers increasingly rely on imported synthetic fertilizer and feed. The uncertainty of global
17 oil supply, and indirectly inputs, calls into question the robustness of the beef farming system in Alentejo,
18 defined as the capacity of the system to sustain its function (beef production) in spite of a disturbance
19 (decreased input availability). An additional challenge is the need for reducing greenhouse gas emissions to
20 meet decarbonization goals. At present, these challenges are being addressed through management practices
21 such as expanding areas of high-yield sown biodiverse pastures and fattening steers partially on grass rather
22 than concentrates. These practices have shown to reduce greenhouse gas emissions, but their effect on the
23 robustness of beef production when inputs are scarce is unknown. To fill this gap, we adapted a dynamic
24 nitrogen mass flow model to assess herd dynamics and calculate a greenhouse gas emissions balance. We
25 applied the model for seven scenarios corresponding to different combinations of management practices over
26 fifty years with increasing input constraints. We estimated, without changes and without constraints, a
27 greenhouse gas balance of 55 kgCO₂-e kg carcass⁻¹ year⁻¹ (100-years global warming potential). Without
28 changes but faced with constraints, meat production dropped 60% (low long-term robustness) in 50 years while
29 increasing by 17% the greenhouse gas balance. Our results show that a combination of high-yield legume-rich
30 pastures, maximization of grass intake, herd size reduction, and increased animal productivity allowed the
31 smallest reduction of meat production (28%) and largest greenhouse gas emission reduction (30%, i.e., 38.9
32 kgCO₂-e kg carcass⁻¹ year⁻¹). Of the combinations studied, it was the best at mitigating the trade-off between
33 robust meat production and climate change mitigation.

34 2 Keywords

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

37 3 Introduction

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

47 In the Portuguese region of Alentejo, grass-based BCFS are part of *Montado* ecosystems. These ecosystems
48 are extensive dry woodland, in which low-density forests co-exist with grassland understory, the latter often
49 grazed by sheep and cattle (Figure 1) (Pereira et al. 2009). The agricultural sector, including beef production,
50 is economically important in Alentejo, representing more than 11% of the total gross value added (Instituto
51 Nacional de Estatística 2020). Alentejo is the main beef production region in Portugal (more than 45% of the
52 cattle population in Portugal is in Alentejo – Instituto Nacional de Estatística (2020)), exporting within Portugal
53 and to other European and Middle Eastern countries (Araújo et al. 2014). However, it is also among the most
54 desert regions in Europe and vulnerable to any decline in imported agricultural inputs arising from oil price
55 increases. Additionally, BCFS in Alentejo contributes approximately 30% of the greenhouse gas (GHG)
56 emissions of the Portuguese agricultural sector, mainly from enteric fermentation (APA 2018). The Portuguese
57 government has set the reduction of CH₄ emissions from enteric fermentation as a policy goal, aiming to
58 decrease the beef cattle population by 25% by 2050, while increasing the productivity of beef cattle to
59 compensate for the decreased meat production caused by the reduction of the number of heads (Republica
60 Portuguesa 2019). Therefore, BCFS in Alentejo face the double challenge of ensuring robustness of their meat
61 supply to mitigate the effects of increased energy costs while reducing GHG emissions. Following Meuwissen
62 et al. (2019), by robustness we mean the capacity of a farming system to deliver its functions in spite of a
63 disturbance, without changing its configuration (definition also coherent with Anderies et al. (2002); Accatino
64 et al. (2014); Pinsard et al. (2021)).



65

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

66 Two promising management practices have been partially adopted by Alentejo farmers seeking to reduce GHG
67 emissions. They can also contribute to climate change adaptation and to improving BCFS economic viability.
68 These practices are: (a) shifting low-yield semi-natural pastures to sown biodiverse pastures rich in legumes
69 (Morais et al. 2018; Teixeira et al. 2018b), and (b) finishing steers on grass rather than on energy and protein
70 concentrates (Costa et al. 2012). Sown biodiverse pastures, mixes of up to 20 different high-yield grasses and
71 legume seeds are more productive than natural pastures (Teixeira et al. 2011; Valada et al. 2012; Proença et al.
72 2015; Moreno et al. 2021). Finishing animals on grass reduces the cost of feeding and improves animal health
73 and welfare (Hocquette et al. 2014) but can also increase CH₄ emissions from enteric fermentation due to the
74 lower digestibility of grass (IPCC 2019a). The two practices are sometimes implemented jointly, but trade-offs
75 may occur between meat production and climate change mitigation. A dynamic modeling approach would be
76 useful to study the robustness of meat production to increasing prices of fossil-fuel intensive inputs while
77 reaching GHG emission reduction targets for Alentejo BCFS.

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

87 4 Materials and methods

88 4.1 Model overview

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

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

103

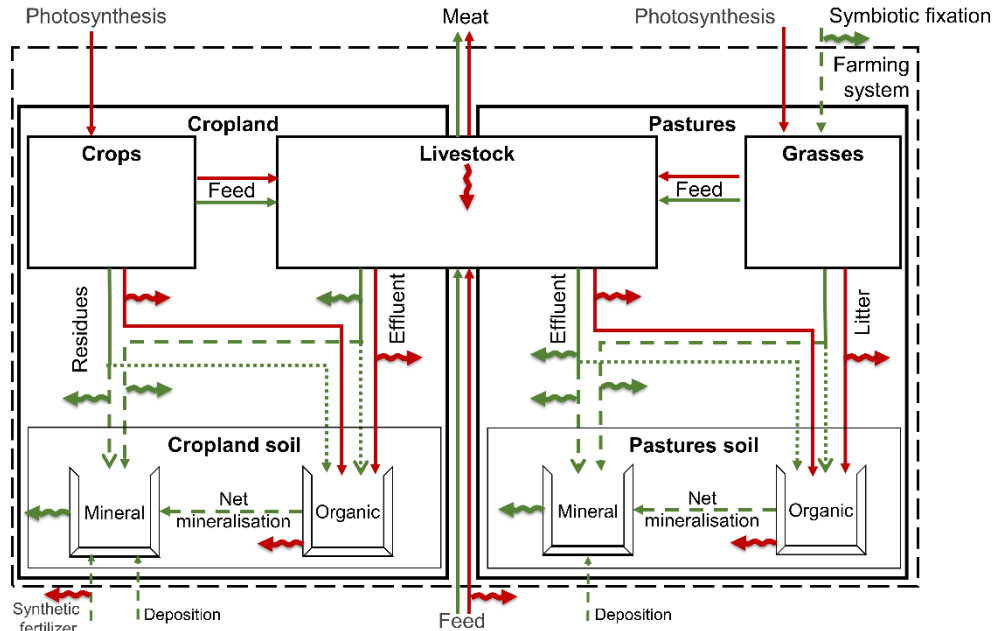


Figure 2. Conceptual scheme of the model. Boxes represent compartments and arrows are the nitrogen (in green) or carbon flows (in red). Nitrogen flows are: mineral (dashed lines), organic (point lines), or mixed (full lines). The wavy arrows represent gaseous or liquid nitrogen or carbon losses.

104 4.2 Model description

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

107 4.2.1 Plant

108 Each crop or pasture type i has a set of traits (assumed constant) useful for calculating biomass production
109 (following Clivot et al. (2019)): area, typical yield of harvested/grazed organ y^{TYP} [kg fresh matter ha⁻¹ year
110 ⁻¹], harvest index, consumption index (the part effectively grazed) for pastures, shoot-to-root ratio, nitrogen and
111 carbon contents of the different parts of the plant, humification coefficients for the plant residues, the nitrogen
112 quantity fixed by legumes per hectare and the share of digestible energy for beef of the edible part. We assumed
113 that yield $y_{i,t}$ [kg fresh matter ha⁻¹ year⁻¹] increases linearly from 0 to the typical yield and then it saturates:
114 $y_{i,t} = \max\left(y_i^{TYP}, \dot{n}_{i,l,t}^{Fert,Av} * \frac{y_i^{TYP}}{\dot{n}_{i,l}^{TYP}}\right)$, where $\dot{n}_{i,l,t}^{Fert,Av}$ is the soil mineral nitrogen available and $\dot{n}_{i,l}^{TYP}$ the soil
115 mineral nitrogen needed by a plant to reach the typical yield (both in kgN ha⁻¹ year⁻¹). Nitrogen surplus is lost
116 to the environment. Crop residues from croplands can be used as feed in the barn, if allocated to the livestock
117 rather than buried in the soil.

118 4.2.2 Soil

119 The variables characterizing the soil compartment for each land use l are the active organic nitrogen stock ,
120 the active organic carbon stock $c_{l,t}^{Soil}$ [kgC ha⁻¹ year⁻¹] and the flow of mineral nitrogen. Organic amendments
121 (crop residues and solid manure) are applied homogeneously the year after. Mineral nitrogen is either
122 consumed by plants or lost at each time step. A part of organic amendments humifies. For carbon, the non-
123 humified part goes to the atmosphere as CO₂. For nitrogen, if the share of the organic amendment that humifies
124 is higher than its nitrogen content, the difference is subtracted from the soil organic nitrogen mineralization,
125 i.e., is immobilized. On the contrary, the mineral share of the organic amendment is available to plants.

126 *Soil organic carbon and nitrogen dynamics*

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

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

128 Input terms are the humified carbon of amendments per hectare (*i.e.*, the aboveground plant residues $\dot{c}_{l,t}^{rA}$,
129 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
130 mineralization of soil organic carbon (being μ_l [-] the mineralization rate).

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

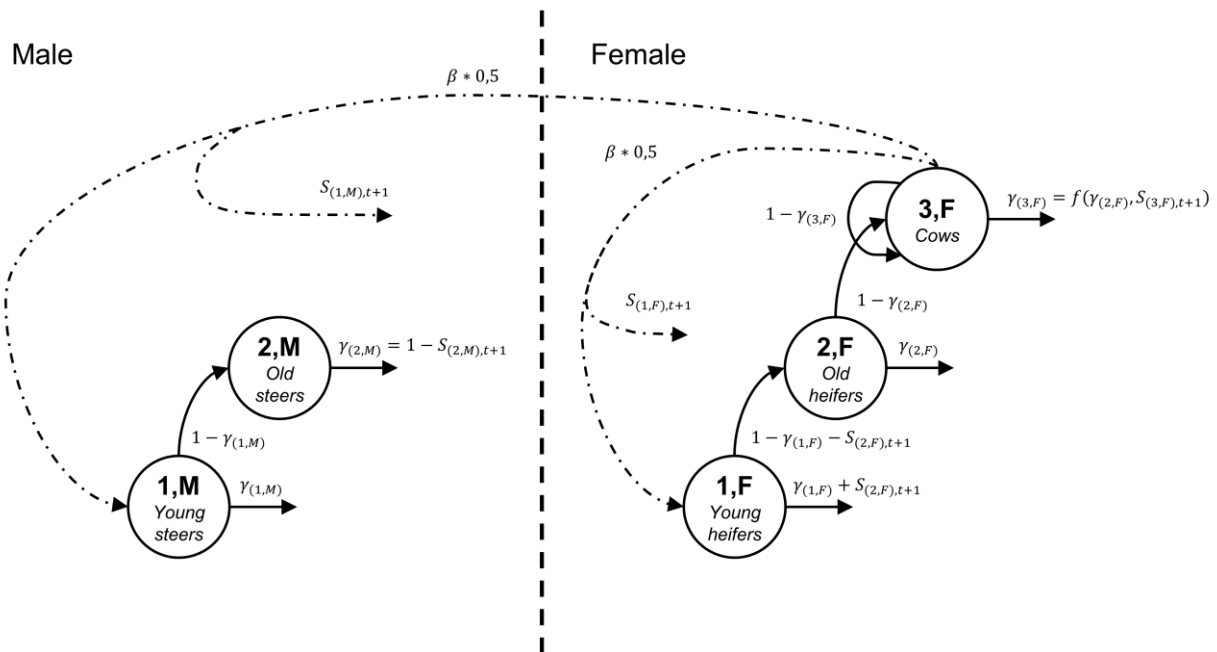
133 **Mineral nitrogen flows and losses**

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

136 Application of nitrogen to the soil leads to losses as N_2O (denitrification and nitrification), NH_3 (volatilization)
 137 and NO_3^- (leaching) that we assessed following a Tier 2 approach using default emission factors from IPCC
 138 (2019) or local emission factors from APA (2018) and Aguilera et al. (2021). Direct N_2O emissions and
 139 leaching occur for all the mineral nitrogen flows applied on cropland or on pastures (soil management).
 140 Volatilization happens during application of organic amendments and synthetic fertilizer. Indirect N_2O
 141 emissions occur during volatilization and leaching.

142 **4.2.3 Beef cattle herd**

143 The herd was divided into five cohorts based on age ($a = 1, < 1$ year old; $a = 2, 1 - 2$ years old; $a = 3, > 2$
 144 years old) and sex ($s = M$ for males, $s = F$ for females): young steers ($1, M$), old steers ($2, M$), young heifers
 145 ($1, F$), old heifers ($2, F$), suckler cows ($3, F$). The quantity of meat produced (in kg carcass) is a function of
 146 the number of heads slaughtered, and their live weight at the beginning of the year or at the end of the year
 147 for old steers. We assumed that the carcass weight of the Alentejo cattle breeds is approximately 60% of the
 148 live weight. Herd dynamics are detailed in Figure 3 and the equations are available as Supplementary Material.



149

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 ($2,M$).

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

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

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

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

164 Excreta generated in housing facilities are stored before being applied to crops the following year. The storage
165 of cattle manure result in direct emissions of N₂O, NH₃, and losses of NO₃⁻. Volatilization and leaching lead to
166 indirect emissions of N₂O. We followed a Tier 2 approach using default emission factors from IPCC (2019).

167 4.2.4 GHG balance

168 The GHG sub-model estimates (following Teixeira et al. (2018)) the emissions of the three main greenhouse
169 gases (CO₂, CH₄, and N₂O; Ritchie and Roser 2020) and develops GHG balance at the BCFS level.
170 Photosynthetic carbon capture during plant growth was obtained following Clivot et al. (2019). We multiplied
171 the carbon content of the different parts of the plant by the crop yield, the harvest index, and the shoot-to-root
172 ratio for plant residues. We considered the carbon content of imported feed in the GHG balance.

173 *CO₂ emission flows*

174 CO₂ emissions from soil organic carbon mineralization were obtained by multiplying the active soil organic
175 carbon stock $c_{t,t}^{Soil}$ by the mineralization rate μ_t (see equation (1)). CO₂ emissions from the mineralization of
176 organic amendments correspond to the total carbon quantity of the amendment deducted from the carbon
177 quantity humified. We considered CO₂ emissions embedded in the imported synthetic fertilizer and feed, due
178 to transportation and production. For synthetic fertilizer, we used an emission factor for Western Europe (in
179 kgCO₂ kgN⁻¹) (FAO 2017). For feed import, we considered CO₂ emissions linked to production as well as
180 transportation by truck. For production, we used an emission factor (in kgCO₂ kg⁻¹) that considered the feed
181 type and the localization of the production of the imported feed for the beef cattle in Alentejo (Morais et al.
182 2018). For transportation, we multiplied the biomass weight by an emission factor (in kgCO₂ (ton.km)⁻¹)
183 (ADEME 2012) accounting for an average distance of 1000 km (roundtrip distance between the north of
184 Portugal, source of most imported feed compounds, and the Alentejo region), and a carbon content of 50% of

185 the biomass imported (TNO Biobased and Circular Technologies 2021).

186 We assessed CO₂ emissions of cattle respiration as the difference between carbon intakes (feed), the quantity
187 accumulated in body tissues, and out-takes (enteric fermentation, excretion, offspring, and milk). The carbon
188 quantities of feed intake and excretion were obtained by multiplying their nitrogen quantities by their
189 respective C:N ratios. Accumulation of feed intake as body weight gain per cattle cohort corresponds to the
190 number of heads multiplied by the variation in live weight and the carbon content of body tissues (considering
191 65% body water content). The carbon in offspring was obtained, considering the initial live weight as 0.

192 *Non-CO₂ emission flows*

193 Methane emissions from cattle manure were calculated using an emission factor for the total quantity of carbon
194 and deducted from the manure carbon to estimate mineralization-related CO₂. Methane emissions from enteric
195 fermentation were computed using the Tier 2 IPCC (2019) equation for non-dairy cattle with the CH₄ yield,
196 linearly interpolated along feed digestibility. Feed digestibility is the sum of the digestible energy per crop
197 consumed by beef cattle herd per feed category, divided by the total gross energy for the feed category
198 considered. We used, for the digestibility per crop, INRAE feed nutritional values for ruminants (Nozière et
199 al. 2018).

200 *Total GHG balance*

201 The annual total GHG balance is the sum of all the GHG flows for one year from both land use and from the
202 cattle herd, converted into CO₂-e using the global warming potential for 100 years (GWP₁₀₀) or the global
203 warming potential star (GWP*) for CH₄. The CO₂ flows captured by plants during photosynthesis are negative
204 values. The use of GWP* for short-lived gases in the atmosphere (approximately 20 years for CH₄) is
205 recommended as it is particularly relevant when assessing their impact on global average temperature over
206 time, or in the case of a net zero-GHG-emissions target (IPCC 2021 - Box 7.3). Indeed, the GWP* allows
207 approximation of the impact of short-lived gases emissions on the climate more accurately than GWP₁₀₀, while
208 the use of GWP₁₀₀ underestimates the impact on the climate when emissions increase exponentially and
209 overestimates it when they are constant or decreasing (Lynch et al. 2020; Thompson and Rowntree 2020). We
210 decided to calculate the GHG balance with both coefficients, to compare the carbon intensity of meat
211 production with other studies, which use the GWP₁₀₀ coefficient. We considered the global warming potentials
212 from the fifth assessment report of the IPCC without carbon feedbacks (Myhre et al. 2013).

213 *4.2.5 Parameters and state variables*

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

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

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

227 The total quantities of above- and belowground residues are initialized using typical values of plant yield in
228 Alentejo (average value over several years in different farms). For both land uses, soil organic carbon stock in
229 the 10 cm soil depth was set equal to the average measured organic carbon content multiplied by the average
230 measured bulk density (12 000 kgC ha⁻¹ for cropland and 11 600 kgC ha⁻¹ for permanent pastures) (Ballabio et
231 al. 2016). We used soil organic nitrogen stocks using a C:N ratio equal to 30 for permanent pastures (Teixeira
232 et al. 2018a) and 10 for cropland (Clivot et al. 2019). For both land uses, we estimated the mineralization rate
233 equal to 13% using the equation of the version 2 of the AMG model (Clivot et al. 2019), and assumed about
234 35% of active soil organic matter stocks in the 10 cm soil depth. We then initialized the active soil organic
235 matter stock in the 10 cm soil depth using the spin-up method (Xia et al. 2012), and considering the
236 immobilization phenomenon for the nitrogen cycle.

237 4.3 Simulations

238 4.3.1 Management practices

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

243 The practice “PP”, is intended to increase productivity. This should make the farms more self-sufficient in
244 fodder while reducing net GHG emissions, as increased biomass production increases carbon sequestration,
245 but also depending on the stocking rate (Abdalla et al. 2018) and the time since sowing (Morais et al. 2018).
246 In 2014, there were 140 000 hectares of sown biodiverse pastures in Portugal (4% of its agricultural land
247 (Teixeira et al. 2015)), and we assumed that this has not changed much. The practice “FF” involves fattening
248 old steers on permanent pastures to reduce input cost and increase farm self-sufficiency. We considered that
249 old steers are full-time kept in housing facilities while other cohorts graze year-round. The practice “LD” is
250 intended to decrease GHG to meet the goals set by the Portuguese government of reducing for instance CH₄
251 emissions from enteric fermentation by 25% from 2020 to 2050 (Republica Portuguesa 2019). The directive
252 suggests “changes in the numbers of the various species” and “productivity improvements through genetics”,

253 which may involve reducing head number, genetically improving animal productivity in the cases where it is
 254 possible, and shifting to more productive breeds to maintain the meat production levels.

255 4.3.2 Simulated scenarios

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

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

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

Scenario	Feed and synthetic fertiliser: Import availability decrease	Permanent pastures: Increase in sown bi- odiverse pasture area share (<i>PP</i>)	Fattened old steers: Shift from a concen- trate-based diet to a forage-based diet (<i>FF</i>)	Animal productivity increase and herd size decrease (<i>LD</i>)
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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

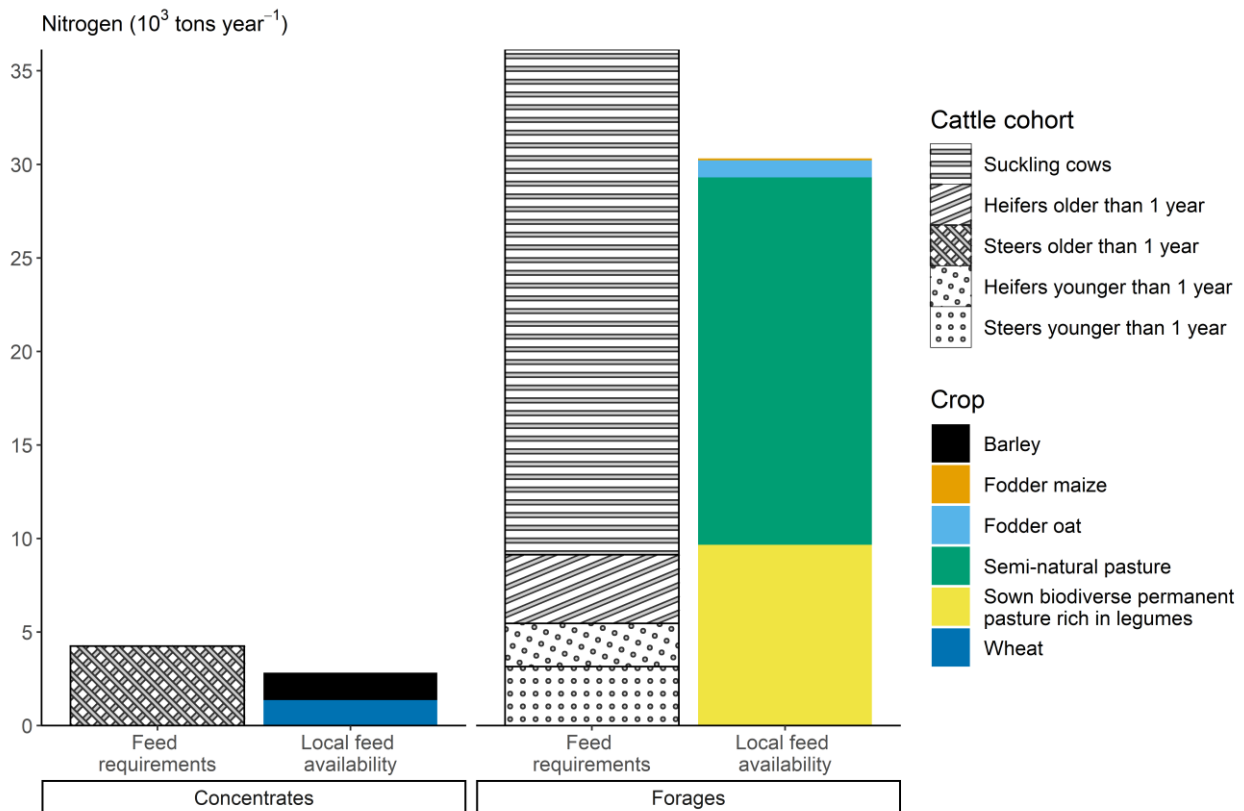
276

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).

277 5 Results and Discussion

278 5.1 Initial feed self-sufficiency

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



287

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.

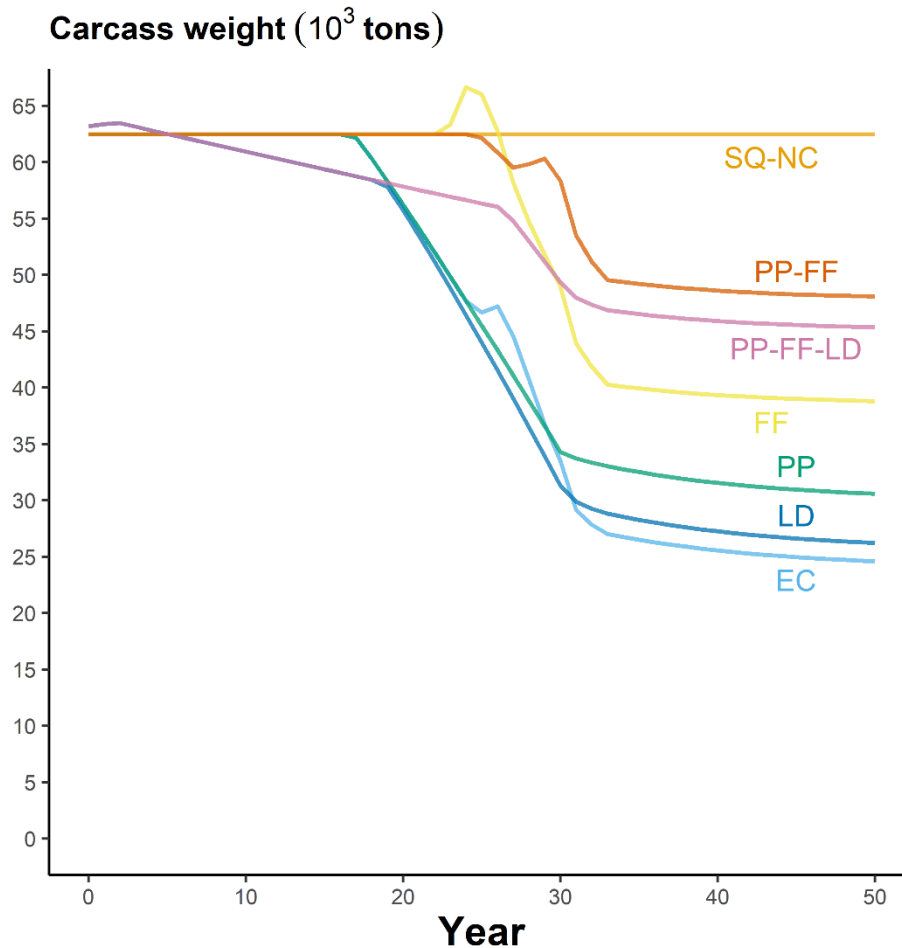
288 Local feed production and the diet of the different cattle cohorts suggested that the BCFS was almost fodder
 289 self-sufficient. This estimate agrees with the survey conducted by Santos et al. (2019), in which 70% of beef
 290 farmers in Alentejo reported being self-sufficient in fodder. Considering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

295 5.2 Temporal dynamics of meat production

296 The time trajectories of meat production varied across the different scenarios (Figure 5). Without a voluntary
 297 decrease in the number of heads (all scenarios except *LD* and *PP-FF-LD*), the trajectories of meat production
 298 overlapped for the first 20 years and were constant over time at more than 60 000 tons carcass. Regardless of
 299 the combination of practices considered, meat production decreased over the 50 years when imports decreased,

300 with an uncertainty interval that increased during the simulation and could go up to -35% and +45% due to
301 uncertainties on biomass production and stocking rate (see Supplementary Material). However, some
302 trajectories were more robust than others. Either meat production began to decline later in the simulation (short-
303 term robustness), or the decline was less at the end of the simulation (long-term robustness).

304 Both short- and long-term, the *PP-FF* trajectory was the most robust and the *EC* and *LD* trajectories were the
305 least robust. In the *PP-FF* scenario, meat production only decreased from year 25 onwards, to approximately
306 48 000 tons after 50 years. As Alentejo is home to more than 60% of Portuguese beef cattle (IFAP 2020), we
307 assume that more than 60% of its beef production is also. With this assumption, the level of production would
308 decline to levels of the early 1970s in the *PP-FF* scenario (Instituto Nacional de Estatística 2020). In the *LD*
309 scenario, the meat production decreased from the beginning of the simulation and overlapped with *PP-FF-LD*
310 scenario until year 18. At the end of the simulation, 26 000 tons of carcass had been produced. In the *PP-FF-
311 LD* scenario, meat production was 45 000 tons in year 50. This was the second most robust scenario in the long
312 term, just a bit less robust than the *PP-FF* scenario. In the *EC* and *PP* scenarios, production started to decline
313 in year 17, while in *PP-FF* scenario, it started in year 25. The production declined in the *FF* scenario in year
314 27, before the decline in *PP-FF* scenario, with a production peak of 67 000 tons of carcass in year 24. This
315 peak of production, that we could also see in scenario *EC* and *FF*, was due to a fodder shortage increasing the
316 culling rate, the slaughter of young steers having not been sufficient (see Figure 2 in the Supplementary
317 Material). We observed a decline in production with increased forage self-sufficiency (scenarios *PP*, *PP-FF*,
318 *PP-FF-LD*), and suggest that the productivity of local crops is high and import of synthetic fertilizers is
319 necessary to maintain crop yields and, indirectly, meat production. Interestingly, we found that the decrease in
320 meat production after 30 years in the *EC* scenario is similar (more than 40%) to that of animal production in
321 the Bocage Bourbonnais (an extensive ruminant farming system whose main production is also beef) in a
322 similar scenario (Pinsard et al. 2021). However, the Alentejo is more robust in the short term than the Bocage
323 Bourbonnais for a nitrogen productivity twice as low (Jouven et al. 2018).



324

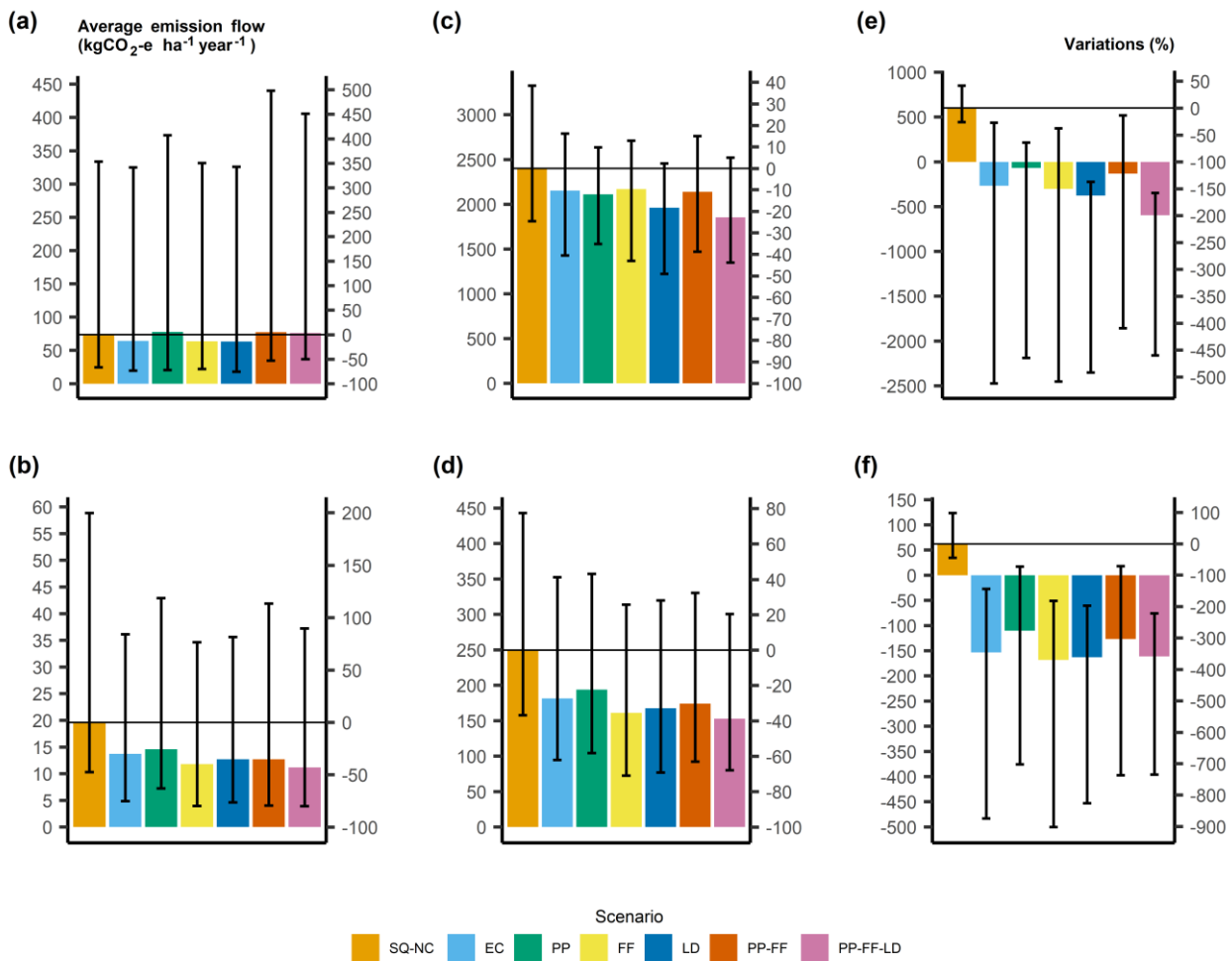
Figure 5. Meat production in the different scenarios over 50 years as predicted by the model. The SQ-NC scenario is the baseline scenario; the status quo with no challenge or change in management practices. In the EC scenario, the challenge is implemented with no management practice. In the PP scenario 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.

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

332 5.3 GHG emissions

333 5.3.1 Per emission flow

334 Nitrous oxide emissions from soil management was the largest N₂O flow over the 50 years (~70 kgCO₂-e ha⁻¹
 335 year⁻¹) (Figure 6a). The N₂O emission flow from manure management accounted for about 20 kgCO₂-e ha⁻¹
 336 year⁻¹ (Figure 6b). Enteric fermentation was the largest CH₄ emission flow (~580 kgCO₂-e ha⁻¹ year⁻¹ with the
 337 GWP* and ~2 330 kgCO₂-e ha⁻¹ year⁻¹ with the GWP₁₀₀) (Figure 6c). The CH₄ emission flow from manure on
 338 management accounted for about 60 kgCO₂-e ha⁻¹ year⁻¹ with the GWP*, and about 240 kgCO₂-e ha⁻¹ year⁻¹
 339 with the GWP₁₀₀ (Figure 6d).



340

Figure 6. Annual average greenhouse gas (GHG) emission flows for the different scenarios for the 50-year simulation time. (a) N₂O emissions from soil management (b) N₂O emission flow from manure management (c) CH₄ emission flow from enteric fermentation with the GWP¹⁰⁰ metric (global warming potential over 100 years) (d) CH₄ emission flow from manure management with the GWP¹⁰⁰ metric (e) CH₄ emission flow from enteric fermentation with the GWP* (short-term global warming potential) metric (f) CH₄ 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

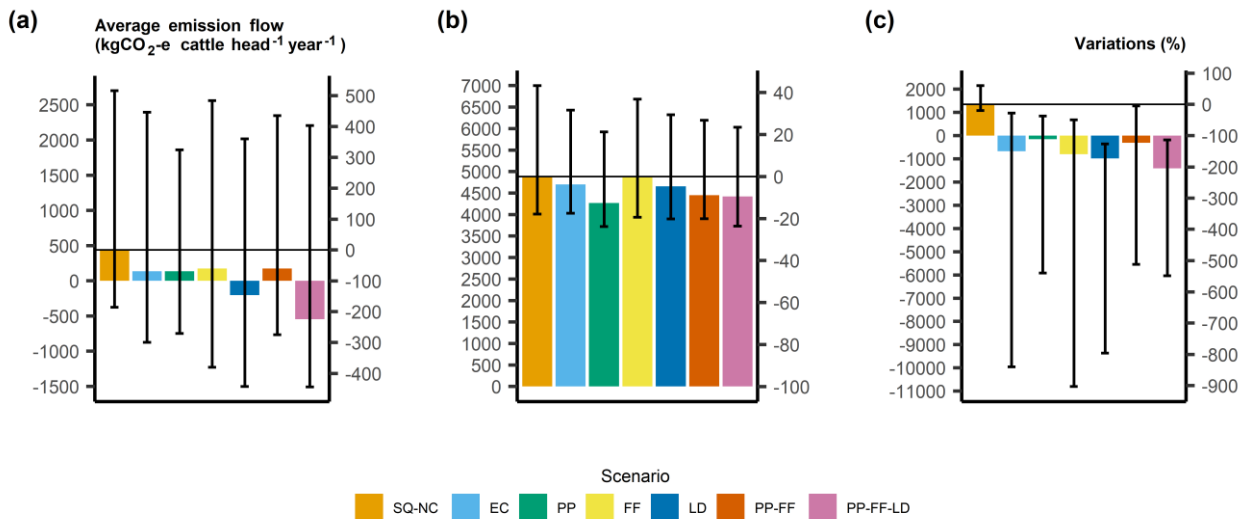
decrease). The error bars represent the minimum and maximum values of a global sensitivity analysis (100 iterations - parameter value ranges are in Supplementary Material).

341 In case of increased pasture productivity (*PP*, *PP-FF* and *PP-FF-LD* scenarios), the 50-year annual average
342 N₂O emission flows from soil management was slightly higher than in the baseline scenario (*SQ-NC*) (by 5%)
343 (Figure 6a). The increase in N₂O emissions from soil management was related to the shift to sown biodiverse
344 pastures, which led to an increase in mineral nitrogen flow in the permanent pastures soil (Teixeira et al.
345 2018a). In all the scenarios with the challenge, the 50-year annual average N₂O emissions from manure
346 management were between 25% and 45% less than in the baseline scenario (*SQ-NC*) (Figure 6b). This decrease
347 is a proxy for the decrease in the number of livestock or the decrease in feed consumption by old steers due to
348 the lack of available feed (see Supplementary Material – section “Results”).

349 In all the scenarios with the challenge, the 50-year annual average CH₄ emissions from enteric fermentation
350 were lower than in the baseline scenario (*SQ-NC*) (Figure 6c). Methane emission flow from enteric
351 fermentation was the highest in the *PP* and *PP-FF* scenarios among all the scenarios with the challenge, when
352 considering both GWP₁₀₀ and GWP* metrics. This is due to a robustness of the livestock number both on the
353 short-term and on the long-term (see Supplementary Material – section “Results”) and to a diet with more
354 fiber, source of lower digestibility (Beauchemin et al. 2008; de Vries et al. 2015; Nozière et al. 2018; McAuliffe
355 et al. 2018). The CH₄ emission flow from enteric fermentation was the lowest in scenarios *LD* and *PP-FF-LD*
356 when considering both GWP₁₀₀ and GWP* metrics. The CH₄ emission flow from enteric fermentation was
357 lower in the *PP-FF-LD* scenario compared to the *LD* scenario due to a slightly higher digestibility of sown
358 biodiverse pastures compared to semi-natural permanent pastures. The global sensitivity analysis showed that
359 the uncertainty range was the highest for that emission flow (± 500 kgCO₂-e ha⁻¹ year⁻¹ with GWP₁₀₀ and down
360 to -2 500 kgCO₂-e ha⁻¹ year⁻¹ with GWP*) as livestock number reduction can be important with lower feed
361 self-sufficiency. The annual average CH₄ emissions over the 50-year simulation from manure management
362 were always lower than those in the baseline scenario (*SQ-NC*) (between 20% and 40% with GWP₁₀₀) (Figure
363 6d). The lower the head number after 50 years, the lower this emission flow with the GWP* (see
364 Supplementary Material – section “Results”).

365 5.3.2 Total balance

366 In the baseline scenario in total, the 50-year annual average CO₂ balance, considering only CO₂ flows, was
367 approximately 420 kgCO₂-e head⁻¹ year⁻¹ (Figure 7a). The 50-year annual average total non-CO₂ GHG balance
368 was approximately 1 300 kgCO₂-e head⁻¹ year⁻¹ with the GWP* and 4 800 kgCO₂-e head⁻¹ year⁻¹ with the
369 GWP₁₀₀ (Figure 7b).



370

Figure 7. Annual average greenhouse gas (GHG) balances for the different scenarios for the 50-year simulation time. (a) Total CO₂ balance. (b) Total non-CO₂ GHG balance with the global warming potential over 100 year (GWP¹⁰⁰) metric (c) Total non-CO₂ GHG balance with the short-term global warming potential (GWP*) metric. Total CO₂ balance is the sum of CO₂ emission flows. The total non-CO₂ GHG balance is the sum of N₂O and CH₄ 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).

371 Total CO₂ balance in all scenarios was lower than in the baseline scenario and negative in scenarios with
 372 reduced head number (LD and PP-FF-LD scenarios) (Figure 7a). However, the uncertainty range is wide in
 373 all the scenario (up to 2 500 kgCO₂-e head⁻¹ year⁻¹) due to uncertainties on the emission factors of the imported
 374 feed and synthetic fertilizer. In scenario PP, in which pasture productivity increased, the total CO₂ balance
 375 decreased by about 70%, despite a constant number of grazing livestock (see Supplementary Material – section
 376 “Results”), due to an increase in soil carbon stocks in grasslands (Teixeira et al. 2018a) and a decrease in fodder
 377 imports. The balance was slightly higher in FF and PP-FF scenarios than in the PP scenario, although the soil
 378 organic carbon stocks increase is similar, because the feed import, which is source of net CO₂ emissions, is
 379 higher.

380 Total non-CO₂ GHG balance was lower (or equal) in all scenarios than in the baseline scenario, with both GWP
 381 metrics (Figure 7b). The decrease of head number coupled to animal productivity increase (LD and PP-FF-
 382 LD scenarios) reduced total non-CO₂ GHG balance the most, more than 200% from the baseline scenario with
 383 GWP*. This result is explained because a decrease in herd size coupled with an increase in individual
 384 productivity will inevitably reduce CH₄ from enteric fermentation without increasing N₂O emissions (Herrero
 385 et al. 2013; Ripple et al. 2014).

386 5.4 Total GHG balance versus meat production robustness

387 There was a strong trade-off between total GHG balance and robustness of meat production that varied with
388 simulation time. Some efficiency gains were possible, depending on the combination of management practices
389 changes put in place. However, maintaining meat production prevented strong reductions of GHG emissions
390 (with the GWP₁₀₀ metric), and GHG emission reductions established in policy objectives were only possible
391 with reductions of meat production.

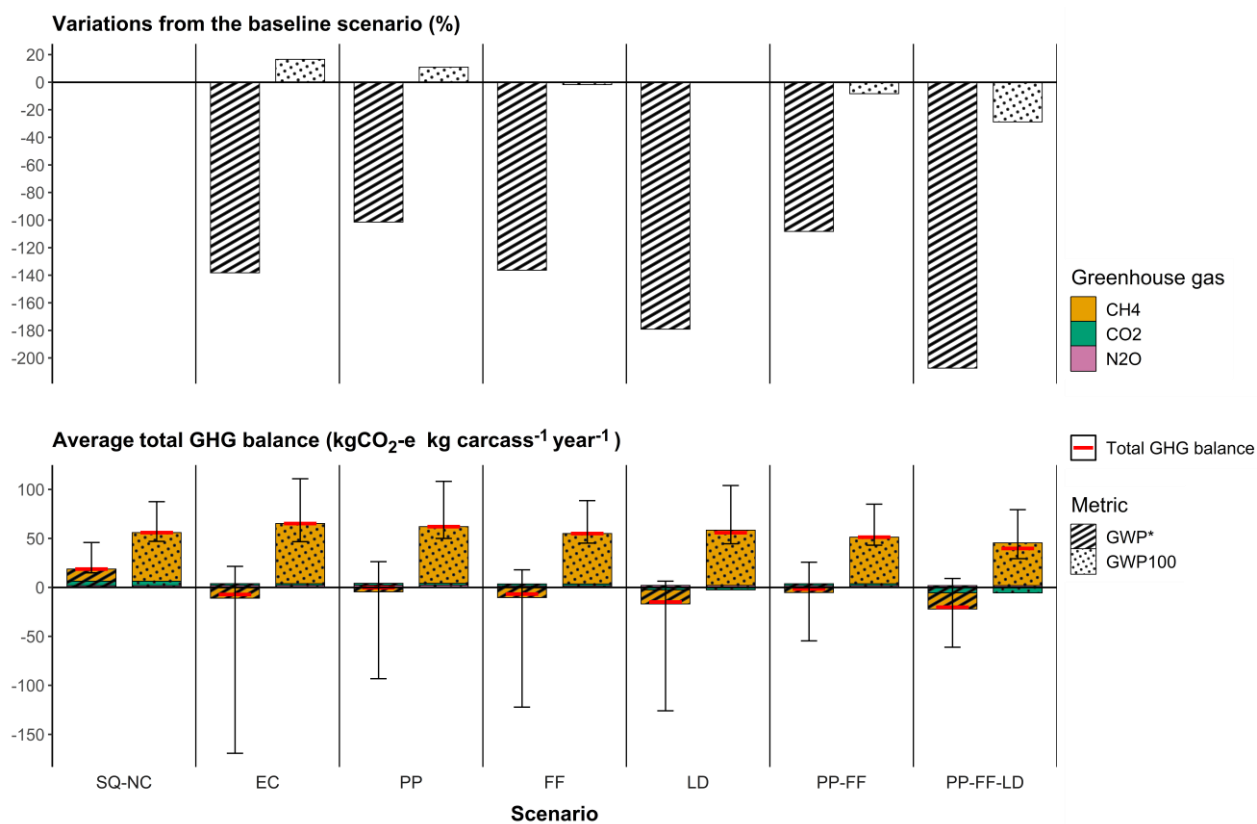
392 In scenarios without reduction in head number (*EC*, *PP*, *FF*, and *PP-FF* scenarios), with the GWP₁₀₀, the annual
393 average total GHG balance (in kgCO₂-e kg carcass⁻¹ year⁻¹) was higher than or slightly lower to the baseline
394 scenario (between +17% and -8%), while with the GWP* it was lower than the baseline scenario (between -
395 3% and -40%) (Figure 8). In *LD* and *PP-FF-LD* scenarios, with the GWP₁₀₀, the annual average total GHG
396 balance was equal or lower than the baseline scenario, down to -30%, while with the GWP*, the decrease
397 reached about -110%. The global sensitivity analysis showed values down to -800% with GWP* with a
398 parameter set giving a low feed self-sufficiency (e.g., lower forage digestibility, lower biomass production,
399 lower stocking rate – see Supplementary Material) and a high livestock number reduction (and thus a lower
400 meat production).

401 The annual average total GHG balance per unit of meat produced was about 55 kgCO₂-e kg carcass⁻¹ year⁻¹
402 with the GWP₁₀₀ in the baseline scenario (between 45 and 80 kgCO₂-e kg carcass⁻¹ year⁻¹ in the uncertainty
403 range), in line with the median value of GHG balances of beef production (all types of beef production systems)
404 collected by Poore and Nemecek (2018), assuming 25% protein in beef meat and a carcass to fat and bone-
405 free-meat yield of 70% (52.5 kgCO₂-e kg carcass⁻¹ year⁻¹ – mean equal to 87.5 kgCO₂-e kg carcass⁻¹ year⁻¹).
406 However, this estimate is much higher than past estimates for this farming system in Portugal or for similar
407 farming systems in Spain, Europe, Brazil, USA or Thailand where the estimates (in kgCO₂-e kg carcass⁻¹ year⁻¹
408 ¹ – we assumed a live-weight to carcass yield of 60%) are respectively 37.7 (Teixeira et al. 2018a), 29.6, 33.3
409 (Eldesouky et al. 2018; Reyes-Palomo et al. 2022), 21-28 (Weiss and Leip 2012), 37.5 (Dick et al. 2015), 32
410 (Pelletier et al. 2010), 23.3 (Ogino et al. 2016). This difference is mainly explained by the large methane flow
411 from enteric fermentation estimated in this study (Tier 2 approach) due to the low digestibility of the grazed
412 grass and the fact that the main feed intake is forages (except for steers in some scenarios). Regarding the
413 latter, unsurprisingly it represents the largest GHG flow in all scenarios. It amounted more than 90% of the
414 non-CO₂ GHGs in the baseline scenario as in Reyes-Palomo et al. (2022) for a similar BCFS. However, this
415 share is larger than in other GHG balances of this or similar farming systems (between 45% and 65%)
416 (Eldesouky et al. 2018; Teixeira et al. 2018a) due to lower N₂O flows.

417 The annual average total GHG balance per unit of meat produced was less than 20 kgCO₂-e kg carcass⁻¹ year⁻¹
418 ¹ with the GWP* in the baseline scenario. The more than 2-fold difference between GWP₁₀₀ and GWP*
419 observed while CH₄ emissions are not changing in the baseline scenario, shows how much GWP₁₀₀ leads to an
420 overestimation of the impact of CH₄ emissions on the climate at constant or decreasing rate of emissions.

421 The annual average total GHG balance per unit of meat produced was lower than in the baseline scenario in
 422 all the scenarios when GWP* was considered (negative values), but not always when GWP₁₀₀ was considered
 423 (Figure 8). In the scenarios without reduced animal numbers (*EC*, *PP*, *FF*, and *PP-FF* scenarios), the total
 424 GHG balance per unit of meat produced when GWP₁₀₀ was used was higher or slightly lower than in the
 425 baseline scenario. In other words, the metric used determined whether we estimated an increase or decrease in
 426 net GHG emissions per unit of meat produced compared to the baseline.

427 Finally, both with GWP₁₀₀ and GWP*, the total GHG balance per unit of meat produced was the lowest in the
 428 *LD* and *PP-FF-LD* scenarios (respectively -14.8 and -20 kgCO₂-e kg carcass⁻¹ year⁻¹ with the GWP* metric).
 429 This can be explained by the decrease in CH₄ emissions from enteric fermentation and manure management
 430 which had a positive (cooling) effect on the climate in these scenarios (“negative emissions” in CO₂-e), as the
 431 volume of CH₄ in the atmosphere associated with the BCFS decreased significantly (after 20 years the CH₄
 432 emitted 20 years ago has been converted to CO₂). This phenomenon was captured with the GWP* metric but
 433 not with the GWP₁₀₀ metric (see Supplementary Material – section “Results”). After a 30-year decrease, CH₄
 434 emissions from enteric fermentation stabilized and the earlier positive effect on the climate decreased in the
 435 following 20 years to a new equilibrium with again a negative effect on climate. Thus, a longer time horizon
 436 for the simulations would lead to an increase in the total GHG balance with the GWP* metric without
 437 significantly impacting the total GHG balance with the GWP₁₀₀ metric.



438

Figure 8. The annual average of the total greenhouse gas (GHG) emissions balance for the 50-year simulation, using GWP₁₀₀ and the GWP* per greenhouse gas. Upper panel, variations from the baseline scenario (SQ-NC) in %; Lower

panel, in $\text{kgCO}_2\text{-e kg carcass}^{-1} \text{ year}^{-1}$. (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).

439 Combining all the practices (PP-FF-LD scenario), was the best compromise between meat production
440 robustness and climate change mitigation (with both metrics) over the next 50 years (Figure 5 and Figure 8).
441 However, animal productivity gains targeted by the Portuguese government's roadmap were insufficient to
442 maintain meat production (LD and PP-FF-LD scenarios) (Republica Portuguesa 2019). Increasing the
443 productivity of permanent pastures (e.g., with sown biodiverse pastures) combined with a diet with more
444 forages supported meat production the most and decreased net GHG emissions (Morais et al. 2018), as
445 observed in the PP-FF scenario. However, this was not sufficient for the decarbonization of the sector
446 (considering the GWP_{100} metric), as in any of the scenarios. Indeed, the Portuguese government's roadmap
447 projects a 50% reduction in emissions from agriculture, by decreasing losses of carbon in cropland soils and
448 by increasing carbon sequestration in permanent pastures soils by 2050 compared to 2020 (Republica
449 Portuguesa 2019). However, with the GWP^* metric, a 50% reduction in net GHG emissions in this agricultural
450 sub-sector was largely achieved in all the scenarios with the challenge. In this case, the PP-FF scenario allows
451 for the best combination of climate change mitigation and robust meat production. However, in the long term
452 (by the end of the century and beyond) it will be necessary to decrease the herd size based on the positive $\text{CO}_2\text{-e}$
453 emissions associated with it (CH_4 and N_2O emissions) to maintain a net zero GHG balance for the Portuguese
454 agricultural sector.

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

462 5.5 Implications and limitations of implementing practice changes

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

467 The sowing of biodiverse pastures requires machinery for tillage to prepare the field for sowing and fertilizing
468 (Teixeira et al. 2011). During the process, phosphorus, borax, and zinc sulfate are applied as cover fertilization,

469 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
470 years but may require frequent applications of phosphorus fertilizer and limestone during this time.
471 Considering that energy supply and input prices may be uncertain in the future, the profitability of establishing
472 and maintaining new sown biodiverse pastures may change. Assessing how would require a dedicated
473 economic study of the system that exceeds the scope of this analysis.

474 Fattening old steers on grass takes at least 18 months, longer than it does on concentrates (Keane et al. 2006;
475 Morales Gómez et al. 2021), due to lower nutritional value of grass compared to concentrates (Brosh et al.
476 2004; IPCC 2019a), and the increased energy expenditure of grazing animals (Brosh et al. 2004; IPCC 2019a).
477 We assumed in our model that grass-fattening did not take longer than 24 months. Furthermore, in reality, this
478 practice is limited in recent years, especially in Alentejo, by the increased frequency of droughts due to climate
479 change and resultant decreased forage production (Nardone et al. 2010; Jongen et al. 2013; Scasta et al. 2015;
480 Huguenin et al. 2017). Therefore, without increasing the resilience of permanent pastures to drought,
481 specifically, without increasing sown biodiverse pasture area, the implementation of this practice could harm
482 the robustness of the BCFS. Nevertheless, from an economic perspective, grass-fattening increases self-
483 reliance of the farm and reduces costs (Escribano et al. 2016). The added value at sale may also be greater as
484 it coincides with the preferences of Portuguese consumers (Marta-Pedroso 2008, Banovic 2009).

485 We assumed a 10% increase in animal productivity over 30 years, probably accomplished by transitioning the
486 cattle population in Alentejo towards the most productive breeds (Charolais and Limousin) and away from the
487 current indigenous Portuguese suckler breeds or the Angus breed (Schenkel et al. 2004; Santos-Silva et al.
488 2020). In 2020, however, only 16.3% of the Alentejo cattle population were indigenous Portuguese suckler
489 breeds (pure or crossbreeds) or the Angus breed (IFAP 2020), and 61% were unspecified beef crossbreeds with
490 unknown productivity. However, if the individual productivity of these crossbreeds is close to that of the pure
491 indigenous breeds in Portugal, then an increase in individual productivity at herd level should be possible.
492 Nevertheless, such a change in the composition of the cattle herd would run counter to the approach of
493 preserving the genetic heritage of the indigenous suckler breeds (Araújo et al. 2014), and, even if less
494 productive, native suckler breeds are adapted to the Mediterranean climate and recommended for extensive
495 systems affected by harsh soil and climatic conditions. Although feasible, the productivity of ostensibly highly
496 productive breeds is not apparent in such a climate and these breeds are more susceptible to diseases when
497 changing diets in extensive BCFS (Pereira et al., 2008). Increasing animal productivity facing increasing
498 drought may not only require consideration of herd composition, but also genetic selection of individuals
499 within a pure breed or in the herd and decreasing cow size while increasing herd size (which could also increase
500 methane emissions) (Nardone et al. 2010; Scasta et al. 2016).

501 According to this model, reduction in head number is unavoidable if we are to meet GHG reduction targets
502 (from a GWP₁₀₀ perspective). This is not explicitly mentioned in the Portuguese roadmap for carbon neutrality,
503 which ideally requires measures to encourage and accept a reduction in the beef demand and financial

504 incentives to help professional conversion of some economic stakeholders of the Alentejo BCFS. Moreover,
505 the drop in beef demand would contribute to Portugal's self-sufficiency, *i.e.*, would help to reduce the trade
506 deficit (target commonly mentioned in the government's political statements). In 2020, in Portugal, beef
507 consumption amounted to an average of 20.8 kg inhabitant⁻¹, *i.e.*, approximately 400 g per week (Instituto
508 Nacional de Estatística 2020). The beef production in Alentejo estimated with this model in 2020, with an
509 assumption of 70% carcass/marketable meat yield, is then sufficient for 20% of this national consumption. In
510 case of a meat consumption halving by 2070, in the worst-case scenario (*LD* and *EC* scenarios) beef production
511 in Alentejo would be sufficient for 17% of Portuguese meat consumption, while in the best-case scenario (*PP*-
512 *FF* scenario) it would be sufficient for 33%, a number similar to the 70s-80s (Instituto Nacional de Estatística
513 2020). Despite the limitations, there are levers that could support the successful implementation of these
514 management practices. Portuguese consumers are willing to pay more for meat if it is of better quality, thus
515 making it possible to increase the selling price if the production cost increases (Banovic 2009). Meat from a
516 grass-finished animal is darker, has a stronger taste, and healthier fatty acids; it is indeed preferred by well-
517 informed consumers (Marta-Pedroso 2008). The area of sown biodiverse pastures in 2009-2014 was greatly
518 expanded as a result of the financial and technical support of the Portuguese Carbon Fund (Teixeira et al.
519 2015). Similar schemes could be devised to encourage a decrease in herd size coupled with an increase in
520 individual animal productivity, as well as to encourage farmers to finish steers on grass.

521 5.6 Study and model limitations

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

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

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

537 Regarding carbon sequestration, we found very low values for permanent pastures' soil in *PP* and *PP-FF*

538 scenarios (600 kgC ha⁻¹ over 50 years, *i.e.*, +0.07% of organic matter in the 10 cm soil depth (initial soil organic
539 carbon matter of 1.5%)) compared to the +0.5% of organic matter expected (~7 tC ha⁻¹) from the measured
540 and modeled soil organic matter content in Alentejo pastures (Teixeira et al. 2011) (near estimate in Pelletier
541 et al. (2010) for an improved cow-calf pastures). This significant difference is mainly explained by the
542 assumption of equilibrium at the beginning of the simulations (constant practices the 30 years before the
543 beginning of the simulation) used to determine the stock of active soil organic carbon that led to its
544 overestimation.

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

562 5.7 Future research perspectives

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

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

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

586 6 Conclusions

587 Two critical policy goals in agriculture are to enhance the robustness of meat production to respond to
588 unpredictable supply and price variations of inputs and to reduce GHG emissions. Those two goals were little
589 investigated jointly in previous studies. To fill this gap, we explored in Alentejo BCFS via modeling, whether
590 management practices put in place to mitigate and/or adapt to climate change, alone and in combination, would
591 address both goals. Our results showed that these latter can be potentially in conflict. They also showed that,
592 combined, those management practices mitigated climate change even when the farms faced decreased
593 supplies of synthetic fertilizer and imported feed, while individual practices were insufficient (considering
594 GWP₁₀₀ metric). However, in those cases meat production could not be maintained at the current levels. We
595 found that an option for ensuring the robustness of meat production and maximizing the reduction of net GHG
596 emissions is a combination of all management practices considered here. Nevertheless, herd decrease and
597 individual animal productivity increase would need to be more ambitious for reducing net GHG emissions
598 over the next 50 years to levels compatible with the GHG reduction roadmap of the Portuguese government.
599 From a GWP* perspective, finishing old steers on grass while increasing the productivity of permanent pasture
600 would be enough to promote robust meat production and reduce significantly net GHG emissions (and be
601 compatible with the roadmap). Nevertheless, the pursuit of this net zero emission target for the agricultural
602 sector will still imply, for a longer time horizon, a decrease in the size of the cattle herd.

603 7 Declarations

604 7.1 Funding (information that explains whether and by whom the research was 605 supported)

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618 7.2 Conflicts of interest/Competing interests (include appropriate disclosures)

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

620 7.3 Ethics approval (include appropriate approvals or waivers)

621 Not applicable.

622 7.4 Consent to participate (include appropriate statements)

623 Not applicable.

624 7.5 Consent for publication (include appropriate statements)

625 Not applicable.

626 7.6 Availability of data and material (data transparency)

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

630 **7.7 Code availability (software application or custom code)**

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

633 **7.8 Authors' contributions (include appropriate statements)**

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

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