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Climate-smart grassland use in dry steppes of Russia and Kazakhstan – Assessment of green-house-gas emission dynamics, agricultural potentials and trade-offs

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Abstract. Livestock production systems face multiple challenges under climate change. Traditional systems have to be evaluated with respect to their production as well as their climate mitigation potentials in the future. We investigated grassland-based livestock production options in the dry steppe region in south-western Russia and northern Kazakhstan using the dynamic global vegetation model (DGVM) Lund-Potsdam-Jena-managed Land (LPJmL). The analysis explicitly includes feed-backs between grazing animals and feed quality and quantity and its effects on biogeochemical flows under different management assumptions varying the amount of applied fertilizer and livestock densities. By calculating environmental impacts for a selection of management combinations according to different objectives, we can assess livestock-related GHG emissions of methane, nitrous oxide, and carbon dioxide, as well as nitrogen pollution to the environment. Results show that environmental conditions, even within this relatively homogeneous arid steppe region, do not only affect production potentials but also trade-offs between maximizing productivity and minimizing environmental impacts per product. This leaves an option space of achieving comparatively high production under low environmental costs.

1 Introduction

In semiarid regions, the efficient and targeted use of resources is of particular importance because plant productivity is reduced by several co-limiting factors that influence each other such as water and nutrient availability (Brueck et al., 2010). These regions are often sparsely populated and not very suitable for crop production, so that people often keep livestock with low grazing densities (Steinfeld et al., 2006). Agricultural intensification so far led to increases in livestock production but was usually also unsustainable with negative impacts on the environment like increased greenhouse gas (GHG) emissions, erosion after overgrazing, biodiversity losses, and/or nitrogen pollution (Petz et al., 2014; Reif and Vermouzek, 2019). Climate-smart agriculture is seen as a potential set of sustainable agricultural practices especially in semiarid and arid environments (Murungweni et al., 2016; Abdo et al., 2024) that enables resilient income even under changing climatic conditions (Managa and Nkobole-Mhlongo, 2016). These are tailored to avoid the unproductive loss of water and are at the same time enhancing or at least stabilizing the amount of carbon in the soil and preventing degradation.

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The dry steppes of south-western Russia and northern Kazakhstan are a prominent example for the benefits and disadvantages of agricultural activities in arid and vulnerable steppe vegetation. Here, steppe was converted to cropland after the second world war, forming the Virgin Land Campaign (VLC) area (McCauley, 1976; Wein, 1980). The area is characterized by highly fertile Chernozems (literally "Black Earth") rich in soil organic carbon (Bischoff et al., 2016). However, short vegetation periods and harsh weather limited the aspired grain crop production so that erosion and yield failures were a common problem (Kraemer et al., 2015). Historically, especially in the steppe region of Kazakhstan, wild herbivores (mostly Saiga antelopes, *Saiga tatarica*) and livestock grazed in highly migratory pastoralist systems (Robinson and Milner-Gulland, 2003). The traditional herding systems of sheep, cattle, yaks, goats, horses, reindeer, and camels (Mirzabaev et al., 2016) changed with increasing numbers of Russian settlers in the 19^{th} century to more intensive sedentary systems with additional feed supply (Kerven et al., 2006). Collectivization after 1930 with enforced settlement led to a loss of more than 80% of Kazakh herds and starvation of more than 1 million Kazakhs (Olcott, 1995). When a reduced form of migration was allowed after 1940 until the 1990s, stocking rates were increased and mostly organized in state farms, leading to overgrazing in the 1970s and 1980s (Kerven et al., 2006). Even though the phenomenon of overgrazing is described and livestock production is reported, actual numbers of animals or stocking densities are available only for the entire country of Kazakhstan and not for subareas such as the Kazakh part of the VLC (Robinson and Milner-Gulland, 2003). According to Kharin and Kiriltseva (1988), 30% of the pasture area was degraded but the description of the degradation status differs in the Russian and European literature (Robinson et al., 2003). Although average numbers for animal densities indicate extensive grazing (e.g. one sheep equivalent on two hectares of pasture in Longmire and Moldashev, 1999, in Mirzabaev et al., 2016), the environmental effects of grazing cannot be evaluated from the given information (Campbell et al., 2006).

The collapse of the Soviet Union led also in the VLC area to large-scale cropland abandonment (Schierhorn et al., 2013) due to the transition from state-command to market-driven economies (Meyfroidt et al., 2016). The cultivation of about 74% of the land converted during the VLC era was given up (Rolinski et al., 2021) and secondary vegetation began to re-establish (Schierhorn et al., 2013). At the same time, livestock numbers declined dramatically (e.g. in Kostanay province in northern Kazakhstan by 77% from 3.0 to 0.7 million heads, Kraemer et al., 2015) and grazing pressure was very heterogeneous (Kerven et al., 2021). Since rangelands and abandoned cropland are known to store vast amounts of carbon (Herrero et al., 2009; Kurganova et al., 2014), the potential of the former VLC region for soil carbon sequestration is expected to be high. Using an accounting approach, Kurganova et al. (2015) estimates a potential of 185 Tg carbon per year for the entire abandoned cropland in Russia and Kazakhstan (around 58 Mha). This depends strongly on the further land-use development (Kurganova et al., 2014; Schierhorn et al., 2013).

The transformation of the agricultural sector in Kazakhstan mainly focuses on improving the competitiveness of grain and livestock production systems where aspects of climate-smart practices remain unconsidered (Belaya and Mykhaylenko, 2010) although it is known that an increase in livestock density may impair biodiversity, strengthen climate change, accelerate soil erosion, and decrease water quality (Dorrough et al., 2007; Herrero and Thornton, 2013; Steinfeld et al., 2006). Biodiversity benefits of rewilding and extensive grazing are expected even though the effect of cropland abandonment on the local fauna and flora is considered less beneficial than in tropical regions (Meyfroidt et al., 2016). Thus, the implementation of climate-

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smart practices for the recultivation of abandoned cropland could be of practical interest for political stakeholders (Meyfroidt et al., 2016). This would allow cropland to be cultivated again in a way that fosters production and rural development without compromising soil carbon stocks or biodiversity.

During land cultivation, tillage destroyed the vegetation cover and wind erosion led to a strong decrease of soil carbon (Guggenberger et al., 2020). It remains an open question whether the sequestration potential can be preserved under land use and whether it will be enhanced or weakened by climate change. Field trials showed that reduced soil tillage of cropland and direct seeding practices can reduce wind erosion and enhance soil carbon sequestration (Grunwald et al., 2016). Restoration of former cropland especially in Kazakhstan was pursued in different systems but with diverse success. Near-natural steppe vegetation was reached only under moderate livestock grazing which ensured species-rich grassy vegetation and avoided wildfires due to litter accumulation of non-native herbaceous plants (Brinkert et al., 2016). Grassland's potential to store carbon is affected by climate change but even more strongly by grazing management and biodiversity loss (Bai and Cotrufo, 2022). Pasture management also strongly affects the nitrogen dynamics that can lead to nitrogen pollution, i.e. losses of reactive nitrogen to the environment, as well as nitrogen limitation of productivity (Phohlo et al., 2022).

The dynamics of carbon storage in soils and vegetation in natural and agricultural ecosystems can be studied using simulation models. These can provide useful information by evaluating scenarios of different management systems where assessments are lacking because of missing data (Petz et al., 2014). We study the potential effects of climate-smart techniques with respect to productivity and environmental impacts, by simulating different scenarios of land management and climate change. The productivity of grazing systems is of central interest, as it determines the viability of livestock-based livelihoods. At the same time, environmental impacts of livestock production should be minimized. We thus measure the performance of different management options not only by the overall productivity but also by the environmental impacts per unit of product. The environmental impact is measured by central biogeochemical stocks and fluxes: carbon stocks in soils and vegetation, GHG emissions (including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)), and nitrogen pollution (including leaching of nitrate (NO_3^-), volatilization of ammonia (NH_3), gaseous losses of nitrous oxide (N_2O)). Environmental impacts can be compared between scenarios as absolute values (e.g. total emissions) or relative to livestock productivity.

The role of pasture management is mostly not considered in modeling studies and data on grazing systems are still scarce although grasslands and pastures globally cover nearly twice the area of cropland (Petz et al., 2014; Kuemmerle et al., 2013). Assessments of the carbon dynamics of terrestrial ecosystems mainly investigates scenarios of climate and land-use change (Gasser and Ciais, 2013; Müller et al., 2016; Todd-Brown et al., 2014) at the global scale (Friend et al., 2014). Model simulations have assessed the effects of large-scale cropland abandonment in European Russia (Schierhorn et al., 2013), but the effect of ongoing recultivation and management adaptation have not been addressed. So far, process-based model simulations did not consider changes in grassland management under future climate projections (Rolinski et al., 2021) but insights in management related trade-offs between ecosystem services and productivity are needed to inform decision makers (Petz et al., 2014).

Studying management impacts in disturbance-prone steppe regions necessitates the inclusion of many processes and management techniques into the modeling framework (Petz et al., 2014), e.g. vegetation-soil interactions, the interaction of feed quality and quantity on livestock productivity and grazed biomass (Heinke et al., 2023), as well as nitrogen conversion pro-

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cesses. Recent model developments of the dynamic global vegetation model (DGVM) LPJmL (Lutz et al., 2019; Herzfeld et al., 2021; Porwollik et al., 2022; Minoli et al., 2019; Heinke et al., 2023) enable the assessment of several agricultural management practices. Therefore, agricultural yields, carbon and nitrogen dynamics can be evaluated quantitatively for different management options and also under changing climatic conditions.

Given the role of pasture management for economic income (livestock productivity), as well as the carbon and nitrogen cycles, pasture management can be optimized towards different targets. Here, we assessed pasture management with respect to three different objectives in order to understand the potential of pasture management and to identify synergies and trade-offs between these objectives:

– $\mathrm{Y}_{\mathrm{max}}$: maximize livestock productivity Y

– $\mathrm{EY}_{\mathrm{min}}$: minimize greenhouse gas emissions (measured with the Global Warming Potential of the GHG emissions in CO_2 equivalent GHG emissions E) per livestock product

– $\mathrm{NPY}_{\mathrm{min}}$: minimize nitrogen pollution (total losses of reactive N to the environment) per livestock product

While an analysis along these different objectives provides a broad understanding of the complex interactions and trade-offs, we focus the analysis on two exemplary cases that we assume to be more relevant for practical considerations than the full breadth of results:

– $\mathrm{EY}_{\mathrm{pol}}$: maximize productivity Y below a threshold for greenhouse gas emissions per livestock product

– $\mathrm{NPY}_{\mathrm{pol}}$: maximize productivity Y below a threshold for nitrogen pollution per livestock product

2 Methods

2.1 Study area

The study region in south-western Russia and northern Kazakhstan (Fig. 1) is characterized by a climatic gradient from continental semi-humid in the northern part to semi-arid in the south. The overall low annual precipitation amounts decline from north (500 mm in the eastern and 400 mm in the western part) to south (200 mm) with higher precipitation during the vegetation period in summer and high interannual variability (Afonin et al., 2008; Blinnikov, 2021). The natural vegetation composition is determined by this gradient from forest steppe in the north, to grassland steppe (at around 53° N in the west and 55° N in the east, Tchebakova et al., 2009), to dry to semi-arid steppes in the south (Ogureeva et al., 1999; WWF-Russia, 2018).

The region was subject to the largest conversion of natural ecosystems into cropland during the 20^{th} century (Frühauf et al., 2020). During the Virgin Lands Campaign (VLC) era between 1954 and 1963, about 45 million hectares (Mha) were ploughed and formed a major wheat production area in the Soviet Union (Durgin, 1962; Wein, 1980). Grassland in the region is mostly located in the drier regions in the south, especially in Kazakhstan, and only to limited extent in the eastern part of the VLC

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region (color shading in Fig. 1, details in appendix A) which has implications for the soil carbon development in the region (Rolinski et al., 2021).

After the break-up of the Soviet Union in 1991, changes in the agricultural sector led again to massive land-use changes in the VLC region (Meyfroidt et al., 2016). About 32 Mha of the established cropland in the VLC era was abandoned (Lesiv et al., 2018). Either secondary steppe vegetation developed (Schierhorn et al., 2013) on the disregarded cropland or the restoration of steppe vegetation was enabled and the expansion of grassland for extensive grazing or haymaking (Kraemer et al., 2015; Hankerson et al., 2019). The increase in grassland area from 45 Mha in 1980 to 60 Mha in 2000 (Fig. A1a) was located in Kazakhstan and in the western part in Russia enlarging the already substantial grassland shares (Fig. A1d). At the same time, the livestock sector declined dramatically and livestock numbers decreased e.g. in Kazakhstan from 49 to 15 million heads between 1990 and 2000 (Kraemer et al., 2015) accompanied by the reduction in grain and fodder crop production by 54%. After 2000, agricultural activities were supported again from the government and total cropland and livestock numbers slightly increased (Kraemer et al., 2015). Livestock systems in recent years (2023 to 2025) can be described for the Kazakh part using official statistics (Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan, 2025). The number of cows in the 4 northern Kazakh oblasts ranged between 143 and 243 thousand heads of which 65 to 74% are dairy cows and 3 to 35% dual purpose cows. The production systems are mainly organized in smaller units and household farms (for cows 65 to 86% and for dairy cows 77 to 91%).

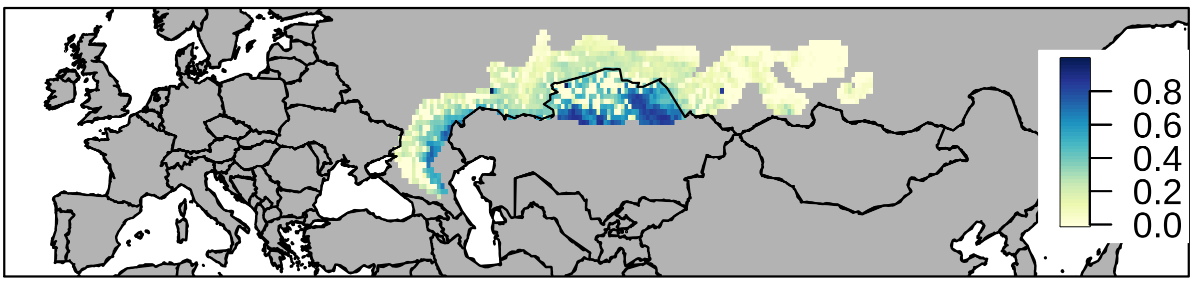

Figure 1. Map of Virgin Lands Campaign (VLC) area in the border region between Russia and Kazakhstan highlighting the fraction of grassland in 2010 between 0% (light yellow) and 100% (dark blue).

2.2 LPJmL

The dynamic global vegetation agriculture and hydrology model LPJmL (Lund-Potsdam-Jena managed land) is comprehensively described (von Bloh et al., 2018; Heinke et al., 2023; Wirth et al., 2024). Results of the model contributed to investigations of terrestrial carbon dynamics under climate and land-use change, both as individual model (e.g., Herzfeld et al., 2021), as well as within model intercomparison studies (e.g., Friedlingstein et al., 2023, 2025). Carbon (C), water, and nitrogen (N) dynamics are tightly coupled in LPJmL through modeled stomatal conductance and N-dependent carboxylation capacity in the photosynthesis and growth modules as well as in soils. Vegetation is represented as plant functional types (PFTs) with three different herbaceous PFTs and eight tree PFTs. Land use is prescribed per fractions of total land in each simulated grid cell. Natural vegetation is assumed to grow in mixed stands, where individual PFTs compete with each other for resources. Managed land (grazed pasture in this case) is simulated in separate simulation units that are initialized with the site conditions of the natural stand upon cultivation according to the land-use input. For more details see Schaphoff et al. (2018) and von Bloh et al. (2018). In this study, the focus is on grassland dynamics under grazing management, where feed quantity (growing above-ground herbaceous vegetation) and quality (protein content, which is approximated from floating C:N ratios) affect livestock productivity. At the same time, livestock stocking densities and feed quality affect the grazed biomass and growth of the herbaceous vegetation. Nitrogen from manure during grazing is directly returned to the soil and constitutes a fertilizer for plant growth, especially in low-input systems. Nitrogen in the soil is subject to water-, material- and temperature-dependent turnover rates. The complete complexity of the grazing-plant growth interaction is described in detail by Heinke et al. (2023). Herbaceous vegetation can also obtain inert atmospheric molecular nitrogen (N_2) through symbiosis with nitrogen-fixing micro-organisms, a process in which part of the plant's assimilated carbon is consumed by the symbionts (for details, see Wirth et al., 2024).

Management practices such as tillage (Lutz et al., 2019) and cover crops (Porwollik et al., 2022), which affect soil carbon dynamics and soil hydrology as well as different grassland management options can be represented (Rolinski et al., 2018; Heinke et al., 2023). Thus, LPJmL is a suitable tool to study the impacts of different grassland management strategies on grassland productivity and the associated carbon and nitrogen cycles. To represent the impact of grazing livestock on grassland in a consistent way, we follow the approach of Chang et al. (2021) and implemented grass intake and conversion dependent on the grass quality expressed as leaf nitrogen content (Heinke et al., 2023). Energy content (MJ day^{-1}) determines the required intake of carbon and nitrogen of an average adult dairy cow of 500 kg body weight. LPJmL only simulates dairy cows as grazing livestock not because the system is deemed most realistic but because it adequately represents the animal-grassland interaction and provides a simple and continuous measure of livestock productivity: milk yield. Simulating beef cattle, a more realistic system for extensive grazing, would require representing herd dynamics, which is currently not implemented in LPJmL. Still, the overall livestock productivity can be reasonably approximated by the simulated yield. Carbon intake is converted to yield, to GHG emissions in the form of CO_2 and methane (CH_4) and excreta in the form of feces and urine. Nitrogen intake is converted to yield and excreta in the form of feces and urine. Excreta are subject to further decomposition and mineralization, leading to additional GHG emissions of CO_2, N_2O, and NH_4 as well as to the supply of reactive nitrogen forms for plant growth (von Bloh et al., 2018; Heinke et al., 2023). For this study, we use LPJmL version 5.6.18 (Schaphoff et al., 2026).

2.3 Input data

Daily weather data for the simulations were based on outputs from general circulation models (GCMs) and comprise daily values of average, minimum and maximum temperatures, precipitation, average wind speed, short-wave and long-wave radiation. These data were supplied via the CMIP6 ScenarioMIP (O'Neill et al., 2016) and provided in bias-corrected form by the 'Intersectoral Impact Model Intercomparison Project' (ISIMIP; isimip.org). We used data from the five standard GCMs in ISIMIP (UKESM1-0-LL (Sellar et al., 2019), MRI-ESM2-0 (Yukimoto et al., 2019), MPI-ESM1-2-HR (Müller et al., 2018),

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IPSL-CM6A-LR (Boucher et al., 2020) and GFDL-ESM4 (Dunne et al., 2020)) for the historical period (1850-2014) and the future period 2015-2100 for the climate trajectory of RCP 7.0 SSP3 (ISIMIP3b; Lange and Büchner, 2021).

For the analysis in the main text, we focus on the results based on MRI-ESM2-1 because they were closest to the average over the 5 GCMs and averaging across results that may differ in sign is not sensible. The variability and standard deviation due to the GCM choice and due to climate trajetories RCP 2.6 SSP 1 and RCP 8.5 SSP 5 is given in the appendix. Atmospheric carbon dioxide (CO_2) concentrations for the historical period and for each of the RCP scenarios were considered as annual global average values (Lange, 2019). Deposition of atmospheric nitrogen in the form of NO_3 and NH_4 is applied using global datasets derived in the ISIMIP3b exercise (Yang and Tian, 2020).

Soil data were derived from the Harmonized World Soil Database (HWSD) version 1.1 (Nachtergaele et al., 2009). Data of the sand, silt and clay content were averaged from the 30 arc second resolution to 0.5° grid cells and reclassified to the respective USDA soil texture class (Soil Science Division Staff, 2017) resulting in twelve productive soil classes and one unproductive class ("rock and ice").

The distribution of managed grassland is prescribed according to the land-use data set described in Rolinski et al. (2021) which includes the cropland expansion period in the VLC era between 1953 and 1964. The data set is based on statistics from the former Soviet Union in the subnational units (oblasts) of the VLC region between 1940 and 2012 (Fig. A1) (Prishchepov et al., 2020). Details of the spatial and temporal grassland area development are described in the appendix (section A).

2.4 Scenario set-up and modelling protocol

Aside from the scenario settings for the management of grassland (see following section), historical simulations were run without additional mineral fertilizer and without tillage practice to represent a baseline run.

Model simulations were run with a daily temporal resolution and on a spatial grid with a resolution of 0.5° × 0.5°. Initial values are not prescribed with current conditions. Instead, runs are started from bare soil in a spinup phase of 8000 years allowing only establishment of natural vegetation. At the end of the spinup simulation, vegetation distribution, carbon and nitrogen stocks and fluxes have reached a dynamic equilibrium. This represents an assumed prehistoric equilibrium without anthropogenic disturbances and under stable climatic conditions. Using this equilibrium state as a starting point for the simulations ensures that the results for carbon and nitrogen fluxes are caused by changes in the climatic input data and prescribed land-use and management options during the simulation period and not by a mismatch between the initial values for carbon and nitrogen pools and the parameterized processes. The derived equilibrium is subsequently disturbed in a second spinup simulation from 1460 onward that introduces historical land use until 1850. Because of the lack of alternative historical data before 1850, climate data from 1850 to 1879 were used in randomly shuffled repetitions for both spinup simulations.

The transient simulation runs from 1851 until 2014 with historical land use, climate dynamics and input data from observations for fertilizer, tillage and land use (section 2.3). We assumed five levels of livestock densities (Tab. 1) which were used for the historical simulations and as starting points for the future period. Each livestock density simulation assumes that livestock was not newly introduced but was present for as long as rangeland was managed in the region. These runs are referred to as 'historical' so that there is a 'historical' simulation for each livestock density considered here.

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For the future time periods until 2100, we conducted simulations on pasture. The 'reference' simulation and all 'management settings' simulations use the same management assumptions on the livestock densities as in the historical period. In the reference run, neither fertilization nor livestock grazing is applied. In the management setting runs, combinations of nine levels of fertilizer application and five levels of livestock density were used. This results in 45 simulations in total (Tab. 1). Fertilizer is applied once per year at the beginning of the growing period.

Table 1. Management settings for grassland management. A livestock unit (LSU) refers to a ruminant animal of 500 kg live weight.

name	period	fertilization (kg N ha^{-1} y^{-1})	livestock density (LSU ha^{-1})
historical	1951–2014	historical (0)	0.2, 0.4, 0.7, 1.0, 1.6
reference	1951–2100	0	0.0
management settings	1951–2100	0, 5, 10, 25, 60, 100, 150, 200, 300	0.2, 0.4, 0.7, 1.0, 1.6

2.5 Metrics for the assessment of management impacts

Table 2. Abbreviations and units of analyzed variables.

Variable	Description	Explanation	Unit
Y	livestock productivity	fat-corrected milk (FCM) produced	kg FCM ha^{-1} d^{-1}
E	carbon dioxide equivalent GHG emissions	GHG emissions of carbon and nitrogen converted to eCO_2 using their GWP	t eCO_2 ha^{-1} y^{-1}
NP	nitrogen pollution	nitrogen losses into the environment	kg N ha^{-1} y^{-1}
EY	E per Y	GHG emission intensity	t eCO_2 kg FCM^{-1}
NPY	NP per Y	nitrogen loss intensity	g N g FCM^{-1}
X_L	livestock related values of variable X	difference of values of the respective management setting run to the reference run without livestock or fertilizer application	same as X
Y_{max}	maximum livestock production	objective of maximum livestock production	kg FCM ha^{-1} d^{-1}
EY_{min}	minimum EY	objective of minimum GHG emissions per livestock production	t eCO_2 kg FCM^{-1}
NPY_{min}	minimum NPY	objective of minimum nitrogen pollution per FCM production	g N g FCM^{-1}
EY_{pol}	maximum Y below a threshold for EY	objective of maximum yield under GHG emission intensity constraint	t eCO_2 kg FCM^{-1}
NPY_{pol}	maximum Y below a threshold for NPY	objective of maximum yield under nitrogen pollution intensity constraint	g N g FCM^{-1}

The selection of the combination of livestock density and fertilizer level is performed per grid cell and for a certain period for each objective. We select combinations per grid cell on the basis of 5-year averages. This takes the reluctance of farmers

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to change management strategies and herd sizes from year to year into account. We evaluate impacts on productivity and environmental impacts for each management setting (Table 1) and climate scenario.

2.5.1 Livestock production Y

Livestock productivity is simulated in terms of a daily conversion of grazed biomass into a product Y. This product is expressed as milk yield (in $\mathrm{gC\ m^{-2}}$ and $\mathrm{g\ N\ m^{-2}}$) although it represents any animal-based protein which results from grass feed intake by ruminants. Thus, we do not represent a dairy system but a proxy for the system's overall productivity without including herd dynamics.

We use fat-corrected milk (FCM), a standardized unit for the produced milk to reflect that the quality of the feed determines the quality of the product in terms of energy and protein content. The simulated milk yield in $\mathrm{gC\ m^{-2}\ year^{-1}}$ is converted by the factor f_{FCM} to $\mathrm{kg\ FCM\ ha^{-1}\ d^{-1}}$ (Eq. 1). This factor is derived by estimating the carbon mass fraction of milk with a fat content of 4% $\omega_{C,milk}$ (Feedipedia, 2020; Heinke et al., 2023) based on relations from Tyrrell and Reid (1965). This way, the value of the produced milk goes along with the nutritional requirements of the animals.

$$\begin{aligned} \omega_{C,milk} &= 0.0695 \\ f_{FCM} &= \omega_{C,milk} \cdot \frac{10^4}{10^3 \cdot 365} \cdot \\ &\quad (0.3994 + 15.0148 \cdot 0.04) \end{aligned} \tag{1}$$

Daily yield per animal unit is derived by dividing the production by the respective livestock density ($\mathrm{kg\ FCM\ LSU^{-1}\ d^{-1}}$).

2.5.2 GHG emissions E

Contributions to greenhouse gas emissions E are reported as carbon dioxide equivalents, eCO_2. E is the sum of carbon (C) related GHG emissions (E_C) and nitrogen (N) related GHG emissions (E_N). E_C includes annual changes in soil and litter carbon content, CO_2 emissions from ruminant respiration, methane (CH_4) emissions from ruminant enteric fermentation and the CO_2 emissions from the energy combustion used for the production of mineral fertilizer. Conversion factors for C (in $\mathrm{gC\ m^{-2}}$) in the form of CO_2 are F_{CO2} and of CH_4 F_{CH4} (Table 3). For mineral nitrogen fertilizer production using the Haber process, we include the greenhouse gas emissions from the energy consumption of the production process with 8.71 kg eCO_2 kg N^{-1} (Wood and Cowie, 2004; Menegat et al., 2022). E_N is determined from N_2O emissions from nitrification and denitrification with the factor F_{N2O} (Table 3). The factors for the contributions to E are selected according to IPCC guidelines (AR6 WG1 of IPCC, 2021). The warming potential of gaseous emissions differs over time for certain gases according to their lifetime (IPCC, 2021) which is especially relevant for methane. We included the factors for the warming potential for 100 years lifetime (Table 3) although we are aware that the warming potential of methane is much higher for shorter time periods (e.g. 79.9 kg eCO_2 per kg carbon for 20 years).

For all simulated variables, the GHG emission balance related to livestock and fertilization (E_L) was derived by subtracting the scenario values from the reference simulation without fertilizer application and without grazing livestock. The livestock-related GHG emissions E_L are calculated and related to the generated product Y for the objective $\mathrm{EY_{min}}$ representing a GHG

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Table 3. Conversion factors for carbon and nitrogen emissions to carbon dioxide equivalent GHG emissions according to IPCC guidelines (AR6 WG1 of IPCC, 2021) and the molar weight of the respective elements. The warming potential for gases is given during a lifetime of 100 years (GWP) in kg eCO_2 per g carbon or g nitrogen.

gas	GWP	unit conversion	factor
CO_2	1	$\frac{C}{CO_2} = \frac{12}{12+2\cdot16}$	$F_{C2O} = \mathrm{GWP}_{\mathrm{CO_2}} \cdot \frac{12+2\cdot16}{12\cdot1000} = 0.0037$
CH_4	27	$\frac{C}{CH_4} = \frac{12}{12+4\cdot1}$	$F_{CH4} = \mathrm{GWP}_{\mathrm{CH_4}} \cdot \frac{12+4\cdot1}{12\cdot1000} = 0.036$
N_2O	273	$\frac{N}{N_2O} = \frac{14}{2\cdot14+16}$	$F_{N2O} = \mathrm{GWP}_{\mathrm{N_2O}} \cdot \frac{16+2\cdot14}{14\cdot1000} = 0.858$

emission intensity EY:

$$EY = E_L/(Y \cdot 365) \quad (\text{kg eCO}_2 \text{ kg FCM}^{-1}). \tag{2}$$

With these definitions, we calculate the target objective $\mathrm{EY}_{\mathrm{min}}$ as minimum EY, i.e. minimum E_L per livestock production.

2.5.3 Nitrogen pollution NP

Nitrogen pollution to the environment, NP, comprises losses of nitrogen to the environment in the gaseous form from nitrification (nitrous oxide N_2O) and denitrification (N_2O), leaching of nitrate (NO_3) into aquatic systems and volatilisation of soil ammonium (NH_4) to atmospheric ammonia (NH_3).

Livestock-related nitrogen pollution, NP_L, is computed by subtracting the scenario's NP from the reference simulation. NP is also related to the production Y for the objective NPY_{min} representing an annual nitrogen use intensity NPY.

$$NPY = NP_L/(Y \cdot 365) \quad \text{in (kg N kg FCM}^{-1}), \tag{3}$$

We use NPY and NP_L to evaluate agricultural practices in terms of their nitrogen impacts. With these definitions, we calculate the target objective $\mathrm{NPY}_{\mathrm{min}}$ as minimum NPY, i.e. minimum NP_L per unit livestock production.

2.5.4 Plausible combinations of management objectives

The three management objectives considered here are almost mutually exclusive: maximizing production leads to highest environmental impacts, while minimizing environmental impacts leads to very low overall productivity – even if normalized per unit of product. In practice, it is more likely that environmental impacts are reduced – but not minimized – by setting targets for the maximal allowed impact. However, such impact thresholds have not been defined by actual policies or regulations so far. Therefore, we only illustrate how thresholds could be selected to form objectives $\mathrm{EY}_{\mathrm{pol}}$ and $\mathrm{NPY}_{\mathrm{pol}}$, respectively. We use exemplary threshold values for EY and NPY, derived as percentiles of the simulated values.

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3 Results

We first present an overview of all simulation results (section 3.1) and show in-depth analyses for the individual optimization targets maximizing productivity (section 3.2), minimizing resource use intensities (section 3.3) and maximizing productivity under additional constraints for environmental impacts (section 3.4).

3.1 Effect of fertilizer application and livestock density

The impact of fertilizer application depends not only on the application rate and livestock density but also on changes in climatic conditions and atmospheric CO_2 concentrations over time (Fig. 2). The livestock production increases with rising fertilizer applications for all livestock densities until an application rate of 100 $\mathrm{kg\,N\,ha^{-1}}$ (Figs. 2a, b). For even higher fertilizer application, the production increases only to a minor extent and only for the highest livestock densities. Livestock production (Fig. 2a, b) is constrained by fertilization levels and livestock densities, so that higher fertilization levels do not translate into higher Y at low stocking densities. However, high stocking densities can lead to reduced Y at low fertilizer levels. The spread of Y values is much higher for high livestock densities (1.6 $\mathrm{LSU\,ha^{-1}}$) in all management settings and time periods as there are favorable as well as marginal areas within the VLC region.

The livestock-related GHG emissions E_L increase more pronouncedly with the livestock density than with the fertilizer application (Figs. 2c, d). Increasing fertilizer rates until 60 $\mathrm{kg\,N\,ha^{-1}}$ resulted in decreasing E_L for the respective livestock density and in increasing E_L for higher fertilizer rates under historical conditions (Fig. 2c). Increasing the livestock density increased E_L strongly for low fertilizer levels and less strongly for high levels of fertilizer. Under future conditions (Fig. 2d), the decline in E_L in the lower fertilizer range is not traceable any more and the variation across the VLC region is higher than under historical conditions. Negative E_L in parts of the VLC region (boxes or whisker extend below the zero line in Fig. 2c and d), i.e. lower GHG emissions than for the reference scenario, are calculated for all management settings but are most pronounced for fertilization levels between 25 and 60 $\mathrm{kg\,N\,ha^{-1}}$ for current conditions and below 25 $\mathrm{kg\,N\,ha^{-1}}$ under future conditions.

Livestock-related nitrogen pollution values NP_L do not differ from zero below fertilizer application levels of 60 $\mathrm{kg\,N\,ha^{-1}}$ in the past (Fig. 2e) and deviate from zero only moderately under future conditions (Fig. 2f). Higher fertilization causes increasing NP_L values which vary slightly with livestock densities. Here, the spread and the median of NP_L decrease marginally with livestock density for each fertilization level. Especially for management settings with high fertilization and low livestock densities the nitrogen supplied was not used by plants and was lost to the environment in form of GHG emissions and leaching. In some cases, NP may even be lower than in the reference run (negative NP_L) especially at high stocking densities and low fertilizer input.

Future responses to fertilizer application under different RCP scenarios (Fig. B1) are qualitatively similar, especially for RCP 8.5 SSP 5. Under RCP 2.6 SSP 1 (Fig. B1a, c, e), Y is lower and NP_L very similar. E_L under this scenario is higher with fertilization values above 100 $\mathrm{kg\,N\,ha^{-1}}$ but substantially negative for the majority of grid cells below 60 $\mathrm{kg\,N\,ha^{-1}}$.

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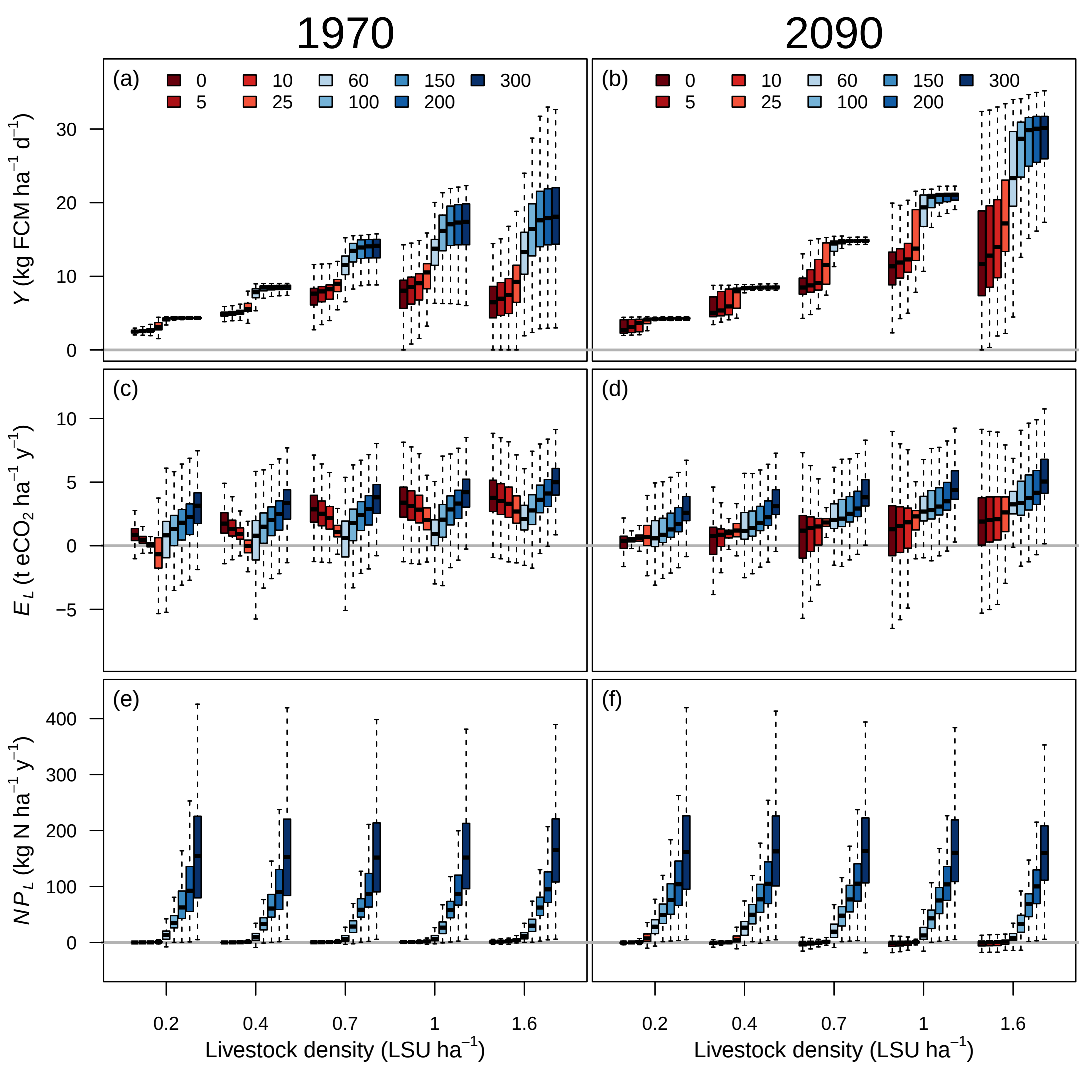

Figure 2. Annual responses to fertilizer application (colors; kg N ha^{-1}) per livestock density in the VLC region for two periods (1970: a, c, e, 2090 under RCP 7.0 SSP3: b, d, f) for (a, b) livestock production (kg FCM ha^{-1} d^{-1}), (c, d) livestock-related GHG emissions E_L (t eCO$_2$ ha^{-1} y^{-1}) and (e, f) nitrogen pollution NP_L (kg N ha^{-1} y^{-1}). For each management setting, boxes enclose the 25% and 75% percentiles of all simulated grid cells in the study area, horizontal lines indicate median values and whiskers extend to 1.5 times the interquartile range.

The impact of increasing fertilizer input and livestock densities is highly non-linear for E_L and NP_L (Figs. 3, C1 and C2). In an exemplary grid cell with medium productivity in the southern Kazakh part of the VLC area (67.75° E, 51.25° N), many fertilizer-livestock density combinations have lower E_L than the reference case (Figs. 3a). Additional fertilizer (colors along the grey lines) leads to a proportional increase in E_L at low stocking densities. At higher stocking densities,

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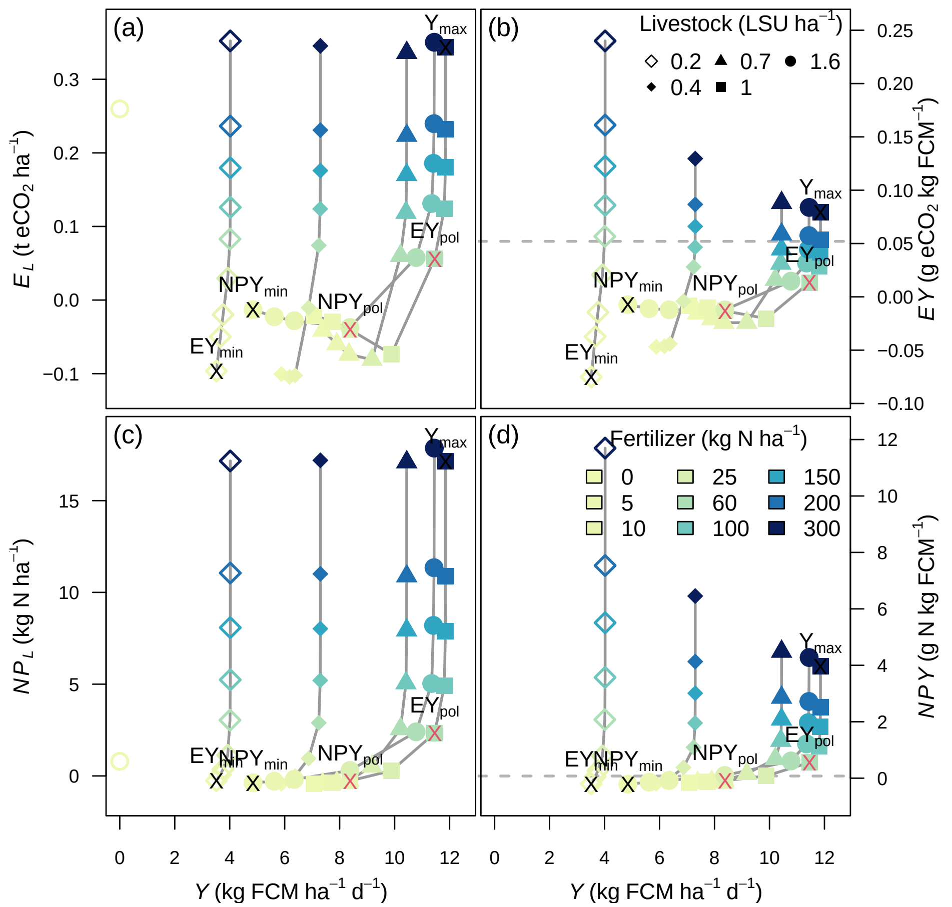

Figure 3. Livestock productivity Y for one grid cell (67.75° E, 51.25° N) versus (a) GHG emissions E_L, (b) GHG emission intensity EY, (c) nitrogen pollution NP_L and (d) nitrogen intensity NPY for all simulation management settings averaged for the period 2005 to 2014. Grey lines combine symbols for the same livestock density for better visibility. Results of objectives are given as crosses with labels above and dashed grey lines give threshold values for the policy objectives.

E_L first declines with increasing fertilizer inputs and only increases at higher fertilizer levels. This GHG emission response to fertilization corresponds with increased Y at higher livestock densities, where greater fertilizer inputs are necessary to realize their production potential (Fig. 3a). At a system-specific turning point (in Fig. 3 between 25 and 100 $\mathrm{kg\,N\,ha^{-1}}$), additional fertilizer no longer contributes to productivity but increases E_L.

GHG emission intensity EY (Fig. 3b) is highest for low livestock densities and high fertilizer levels. Under high fertilization, EY decreases with increasing livestock densities, indicating improved resource use efficiency. Low and even negative EY can be achieved by multiple combinations of balanced fertilizer input and stocking densities. In contrast, minimizing GHG emission intensities (objective $\mathrm{EY_{min}}$) would favor a system with very low productivity at the lowest fertilizer level and stocking density.

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This general patterns also applies to NP_L (Fig. 3c) and NPY (Fig. 3d). Under low fertilization, increasing livestock densities yields minimal production gains, resulting in low NP_L and NPY. Analogous to EY, NPY decreases with increasing livestock density for high fertilizer levels and shows diminishing returns of increasing resource intensities above certain thresholds for fertilizer and livestock densities. The diminishing returns of the nitrogen input can be used to identify management settings that allow for relatively high productivity at low levels of NP_L. Implementing a threshold for EY and NPY (objectives $\mathrm{EY_{pol}}$ and $\mathrm{NPY_{pol}}$) helps identifying the management combination that maximizes production without exceeding these thresholds. For demonstration purposes, we here selected the 20th percentile for EY (0.052 g eCO_2 kg FCM^{-1}) and the 30th percentile for NPY (0.077 g N kg FCM^{-1}) as policy thresholds.

The shape of these response figures change when choosing a highly productive grid cell in the western Russian region (39.25° E, 47.25° N, Fig. C1) or a low productive one in the western Kazakh part (62.25° E, 50.75° N, Fig. C2). However, the general behavior is confirmed and we found the non-linear response in all simulated grid cells.

Negative emissions E_L are calculated exclusively for carbon emissions from the soil. This means that emissions are lower for certain fertilizer applications and livestock densities than in the reference simulation (shown exemplarily for fertilizer levels of 0, 10 and 100 $\mathrm{kg\ N\ ha^{-1}}$ in Table C1). The supply of nutrients with a fertilizer application of around 60 kg N $\mathrm{ha^{-1}}$ avoids nutrient deficiency and provides the basis for enough grassland productivity to increase the livestock density (compare the reduction of vegetation carbon by increasing livestock density at 10 kg N $\mathrm{ha^{-1}}$ by more than 500 $\mathrm{gC\ m^{-2}}$ and at 100 kg N $\mathrm{ha^{-1}}$ by less than 300 $\mathrm{gC\ m^{-2}}$; VegC in Tab. C1). Under these conditions, net primary productivity (NPP) increases with increasing livestock density because grazing constantly removes leaf biomass and reduces maintenance respiration compared to full-grown mature plants. Repeated leaf removal reduces vegetation biomass and leaf litter inputs. However, grazing induces root biomass shedding that replenishes the below-ground litter pool (Bilotta et al., 2007). Reduced litter cover both decreases infiltration and increases evaporation, resulting in lower soil moisture content. Since soil and litter carbon decomposition is mainly driven by moisture in this semi-arid environment, decay rates are reduced and the soil carbon pool remains more stable than in humid environments (residence time of carbon in the soil increases; RT in Tab. C1). Additional C inputs from livestock manure (feces and urine) compensate for approximately 50% of the reduced carbon flux from moribund leaves. The net effect of introducing or increasing the livestock density is reduced carbon emissions compared to the reference run. This reduction results from three mechanisms: enhanced productivity, lower soil respiration and partial compensation of reduced leaf litter fall by manure supply (section 4.1).

3.2 Maximizing livestock productivity

Maximizing production (objective $\mathrm{Y_{max}}$) yields the highest management intensities and environmental impacts in comparison to the other objectives. For this objective, the optimal management combinations vary spatially and over time as changing climatic conditions and atmospheric CO_2 concentrations alter the efficiency of management combinations (red lines in Fig. 4). Selected livestock densities are high and increase over time from 1.3 to 1.6 $\mathrm{LSU\ ha^{-1}}$ (Fig. 4a) and fertilizer levels vary around 240 $\mathrm{kg\ N\ ha^{-1}}$ without a pronounced temporal trend (Fig. 4a). The increasing livestock density enables steadily increasing

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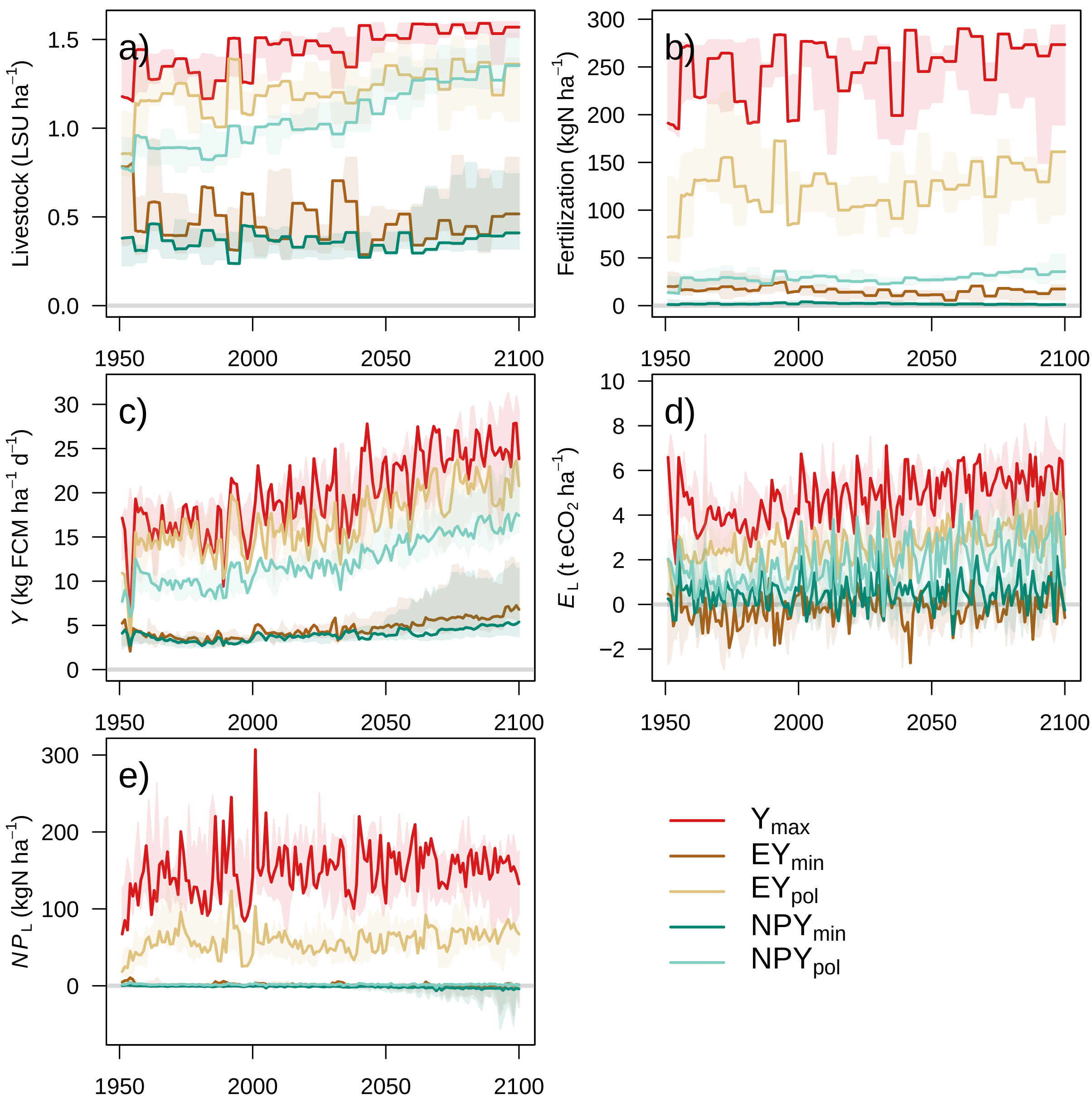

Figure 4. Time series of area-weighted average values in the VLC region between 1950 and 2100 for all objectives (colors) for applied livestock densities (a), fertilizer level (b), the livestock productivity Y (c), the livestock-related values for GHG emissions E_L (d) and the nitrogen pollution NP_L (e). Lines show values for simulation with GCM MRI-ESM2-1 and shaded areas the range for 5 GCMs under RCP 7.0 SSP 3.

production values from 15 kg FCM ha^{-1} d^{-1} in 1950 to 25 kg FCM ha^{-1} d^{-1} in 2100 (Fig. 4c). The resulting E_L (Fig. 4d) and NP_L (Fig. 4e) values consistently exceed those of other objectives throughout the simulation.

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Comparing results across RCP 7.0 (Fig. 4), RCP 2.6 (Fig. D1) and 8.5 (Fig. D2) reveals few differences. For objective $\mathrm{Y}_{\max}$, the livestock production in the second half of the 21^{st} century remains stable for RCP 2.6 (20.7 $\mathrm{kg\ FCM\ ha^{-1}\ d^{-1}}$) and further increases for RCPs 7.0 and 8.5 (25.9 and 26.3 $\mathrm{kg\ FCM\ ha^{-1}\ d^{-1}}$, respectively). The environmental impacts at the end of the century are lowest for RCP 2.6 (E_L of 4.8 $\mathrm{t\ eCO_2\ ha^{-1}}$ and NP_L of 126 $\mathrm{kg\ N\ ha^{-1}}$) whereas E_L is highest for RCP 7.0 (6.1 $\mathrm{t\ eCO_2\ ha^{-1}}$ in comparison to 5.6 $\mathrm{t\ eCO_2\ ha^{-1}}$ for RCP 8.5) and NP_L is highest for RCP 8.5 (154 $\mathrm{kg\ N\ ha^{-1}}$ in comparison to 7.0 with 138 $\mathrm{kg\ N\ ha^{-1}}$).

Summarizing the spatial and temporal averages for four different periods for all objectives (Fig. 5) gives an overview over main impacts of the simulated management objectives. For $\mathrm{Y}_{\max}$, high values for livestock density (Fig. 5a, left bar group) and fertilizer amount (Fig. 5b) correspond to highest production (Fig. 5c). The resulting E_L (Fig. 5d) are also highest. Emissions originate primarily from enteric fermentation (50 to 62%) and the production process of nitrogen fertilizer (32 to 37%), partly offset by soil carbon gains or reduced carbon losses relative to the reference run (-6 to -17%). Nitrogen pollution NP_L (Fig. 5e) is substantial, reaching 54 to 66% of the amount of fertilizer applied (Fig. 5b). NP_L contributions are mainly leaching into surface waters and volatilization of NH_4 into atmospheric NH_3.

Again, comparing the results across RCP 7.0 (Fig. 5), RCP 2.6 (appendix Fig. D3) and 8.5 (appendix Fig. D4) reveals few differences. For objective $\mathrm{Y}_{\max}$, Y remains stable in the second half of the 21^{st} century for RCP 2.6 and further increases for RCPs 7.0 and 8.5 (Tab. C2). These yields are produced under similar livestock densities and slightly different fertilizer levels (9 % less for RCP 2.6 and 4 % more for RCP 8.5 than for RCP 7.0). E_L and NP_L show corresponding differences (21 and 8 % for E_L and 9 and -12% for NP_L compared to RCP 7.0, respectively).

Under $\mathrm{Y}_{\max}$, livestock densities and fertilizer rates (2005-2015) show strong spatial variations (Figs. 6a, f, k, p, u). The northern and southwestern Russian part (intensive management) of the VLC region exhibit high values for both variables, while the Kazakh part shows lower values (Figs. 6a, f). Intensive management in the Russian and northern Kazakh regions (82% of the VLC area), produces high Y values per area (20 $\mathrm{kg\ FCM\ ha^{-1}\ d^{-1}}$) and per animal unit (13 $\mathrm{kg\ FCM\ LSU^{-1}\ d^{-1}}$) causing high GHG emissions (5 $\mathrm{t\ eCO_2\ ha^{-1}}$) and N pollution (150 $\mathrm{kg\ N\ ha^{-1}}$). In the remaining Kazakh region (18% of the area), lower fertilizer and livestock levels are selected (120 $\mathrm{kg\ N\ ha^{-1}}$ and 1 $\mathrm{LSU\ ha^{-1}}$) even for maximizing yield ($\mathrm{Y}_{\max}$), indicating that environmental constraints do not allow for more intensive management here. This results in lower production per area (10 $\mathrm{kg\ FCM\ ha^{-1}\ d^{-1}}$) and per animal (10 $\mathrm{kg\ FCM\ LSU^{-1}\ d^{-1}}$) as well as lower environmental impacts (E_L of 1.7 $\mathrm{t\ eCO_2\ ha^{-1}}$ and NP_L of 49 $\mathrm{kg\ N\ ha^{-1}}$).

Results of the single GCM MRI-ESM2-1 are representative (Fig 6) and are analyzed because multi-modal averages can obscure opposing regional trends. The GCM ensemble mean shows similar spatial patterns (Fig. E1). Deviations between results due to the choice of the GCM (Fig. E2) are small in the productive Russian and northern Kazakh region. However, the differences are considerable in the southern Kazakh part especially for the fertilizer amount applied (standard deviation of 87 $\mathrm{kg\ N\ ha^{-1}}$, Fig. E2f). There, livestock productivity and E_L deviate slightly and NP_L strongly (sd between 70 and 105 $\mathrm{kg\ N\ ha^{-1}}$, Fig. E2u).

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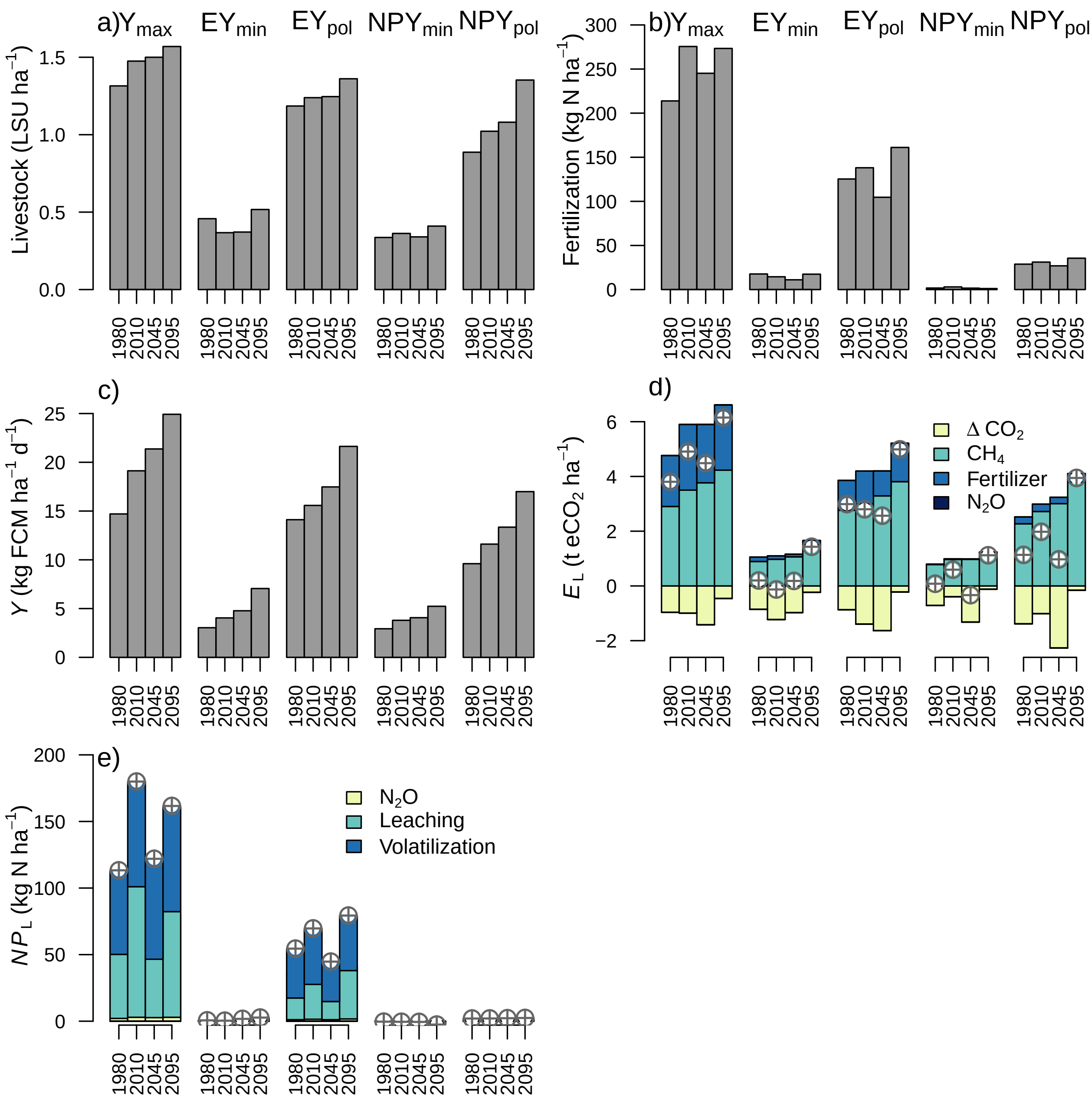

Figure 5. Average livestock-related values in the VLC region for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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3.3 Minimizing impact intensities

For the impact intensity objectives EY_{min} or NPY_{min} moderate livestock densities (about 0.5 and 0.4 LSU ha^{-1} for EY_{min} and NPY_{min}, resp.) and low fertilizer levels (15 and 2 kg N ha^{-1}, resp.) are best suited until 2000 (Fig. 4c). These settings produce substantially lower Y (5.4 and 4.5 kg FCM ha^{-1} d^{-1}, resp.) compared with Y_{max}. Whereas both objectives result in very similar livestock densities, the respective fertilizer application remains below 20 kg N ha^{-1} for EY_{min} and below 1 kg N ha^{-1} when nitrogen pollution intensity is minimized under NPY_{min}. Net GHG emissions are slightly below the values of the reference run for EY_{min} and similar for NPY_{min} (Fig. 4d). Nitrogen pollution values for both objectives are similar to the reference run, though EY_{min} and NPY_{min} differ from each other (Fig. 4e). Compared with other GCMs (shaded areas in Fig. 4), results for MRI-ESM2-1 that are shown in the main text generally fall near the ensemble mean and deviate from the ensemble mean for the selected livestock density (Fig. 4a) and the respective Y only after 2050 (Fig. 4c).

The overview for selected time periods (Fig. 5) shows that for both objectives EY_{min} and NPY_{min} only a third of the livestock density of Y_{max} is selected (22 to 39 %). Fertilizer levels are lowest for NPY_{min} (1%) and reduced as well for

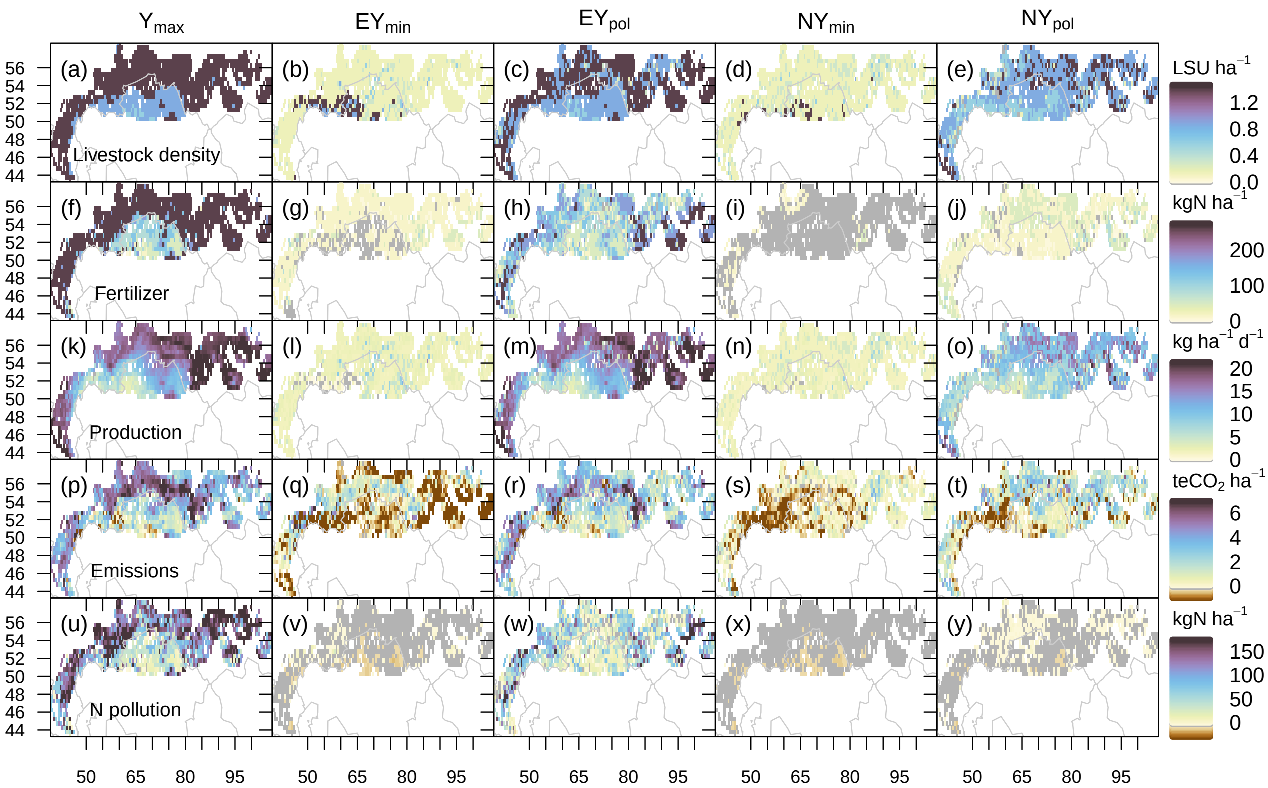

Figure 6. Simulation results for the objectives (columns 1 to 5) in the VLC region between 2005 and 2015 for the selected livestock densities (a to e), the applied fertilizer level (f to j), the livestock productivity (k to o), the GHG emissions E_L (p to t) and the nitrogen pollution NP_L (u to y). Axis ticks and labels denote latitudes and longitudes.

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$\mathrm{EY_{min}}$ (6%) in comparison to $\mathrm{Y_{max}}$. The difference in fertilizer application between $\mathrm{EY_{min}}$ and $\mathrm{NPY_{min}}$ results in low E_L (Fig. 5d) and very similar N pollution values as in the reference simulation (NP_L) (Fig. 5e). In comparison to $\mathrm{Y_{max}}$, E_L is reduced substantially under $\mathrm{EY_{min}}$ (less than 8 %) but there is also a strong reduction under $\mathrm{NPY_{min}}$ despite not targeting GHG emissions (14 %). Similarly, NP_L is reduced strongly under $\mathrm{NPY_{min}}$ (below 0 kg N $\mathrm{ha^{-1}}$) and also for $\mathrm{EY_{min}}$ despite not targeting N pollution (less than 1 %). Under $\mathrm{EY_{min}}$, E_L emissions (Fig. 5d) consist mainly of enteric methane (33 to 55%) and fertilizer production emissions (3 to 6%), largely offset by livestock-related soil carbon gains $\Delta \mathrm{CO_2}$ (-42 to -60%). For $\mathrm{NPY_{min}}$, E_L values are comparable, but enteric methane dominates (54 to 93%) and soil carbon offsets are lower (-19 to -45%).

For objective $\mathrm{EY_{min}}$ low livestock densities (0.2 LSU $\mathrm{ha^{-1}}$) and fertilizer levels (24 kg N $\mathrm{ha^{-1}}$) are selected across most of the VLC region (92 % of the area) (Fig. 6b, g). Under this management, total livestock productivity per area is low (3.4 kg FCM $\mathrm{ha^{-1}}$ $\mathrm{d^{-1}}$, Fig. 6c) but per-animal productivity is high (15.0 kg FCM $\mathrm{LSU^{-1}}$ $\mathrm{d^{-1}}$). Here, the GHG emissions E_L barely deviate from the reference run (0.3 t $\mathrm{eCO_2}$ $\mathrm{ha^{-1}}$, Fig. 6q) and NP_L values are small (1.1 kg N $\mathrm{ha^{-1}}$, Fig. 6v). Only in the south-western Kazakh part (8 % of the area), higher livestock densities (1.5 LSU $\mathrm{ha^{-1}}$) and lower fertilizer levels (5 kg N $\mathrm{ha^{-1}}$) are selected which result in even lower production (0.7 kg FCM $\mathrm{ha^{-1}}$ $\mathrm{d^{-1}}$ and 0.5 kg FCM $\mathrm{LSU^{-1}}$ $\mathrm{d^{-1}}$). Whereas NP_L is similarly low as in the more productive part (Fig. 6v), E_L is even lower than in the reference run (-2.6 t $\mathrm{eCO_2}$ $\mathrm{ha^{-1}}$, Fig. 6q).

Objective $\mathrm{NPY_{min}}$ (minimizing livestock-related nitrogen pollution per unit Y, Fig. 6, column 4) further reduces management intensities and environmental impacts relative to $\mathrm{EY_{min}}$. For this objective, low fertilizer levels (2.2 kg N $\mathrm{ha^{-1}}$) and livestock densities of 0.2 LSU $\mathrm{ha^{-1}}$ (in 74% of the area) or 0.5 LSU $\mathrm{ha^{-1}}$ are selected (Fig. 6d, i). Livestock productivity per area (3.2 kg FCM $\mathrm{ha^{-1}}$ $\mathrm{d^{-1}}$, Fig. 6n) remains low but high per LSU (12 kg FCM $\mathrm{LSU^{-1}}$ $\mathrm{d^{-1}}$). Associated environmental impacts are similar to the reference scenario for GHG emissions (0.3 t $\mathrm{eCO_2}$ $\mathrm{ha^{-1}}$, Fig. 6s) but lower for nitrogen pollution (-0.05 kg N $\mathrm{ha^{-1}}$, Fig. 6x). E_L is highest in a less productive area in the center (3-5t $\mathrm{eCO_2}$ $\mathrm{ha^{-1}}$) and below 0 in most of the VLC region.

The spatial pattern for the selected GCM MRI-ESM2-1 closely corresponds to the GCM ensemble mean (Fig. E1) except for the livestock density and E_L. Average livestock densities in the productive area in southern Kazakhstan are slightly lower than for other GCMs, resulting in the highest inter-GCM variability (sd values above 0.6 LSU). E_L varies across GCMs only in the northern part of the VLC (sd values above 3 t $\mathrm{eCO_2}$ $\mathrm{ha^{-1}}$).

Both impact intensity minimizing objectives result in similar patterns and a considerably lower Y than the other objectives (compare 3.2). Although $\mathrm{EY_{min}}$ and $\mathrm{NPY_{min}}$ target different environmental metrics – E_L and NP_L respectively – both strategies yield reciprocal co-benefits.

3.4 Maximizing production under constraints

Objectives that target compromises between the maximization of productivity and environmental impacts by setting thresholds for impact intensities ($\mathrm{EY_{pol}}$ and $\mathrm{NPY_{pol}}$) lead to less extreme system characteristics. The degree to which multi-objective systems ($\mathrm{EY_{pol}}$, $\mathrm{NPY_{pol}}$) deviate from single-objective optima in terms of Y, E_L and NP_L depends on the selected thresholds

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for EY and NPY. Therefore, the results presented are only illustrative and depend on the arbitrarily chosen thresholds. Threshold-based objectives achieve high production with substantially lower environmental impacts than Y_{max}. Under EY_{pol}, production reaches 80 to 90% of Y_{max} levels while reducing E_L to 55-63 % and NP_L to 34-45%. Under NPY_{pol}, production reaches 56 to 73 % of Y_{max} with even more pronounced impact reductions: E_L at 33-65 % and NP_L at 0-1.5 %. Management intensity shows highly nonlinear effects on productivity and environmental impacts (Fig. 3).

For EY_{pol}, the simulation with the highest production and a GHG emission intensity below 0.052 g eCO2 kg FCM^{-1} was selected. Livestock density under EY_{pol} mirrors that under Y_{max} (Figs. 6c, m), though fertilizer application is lower (between 100 and 220 kg N ha^{-1}, Fig. 6h). Livestock productivity for EY_{pol} shows a similar spatial pattern as livestock density but reaches about 80 % of Y_{max} levels (Fig. 6m).

Under NPY_{pol} (nitrogen pollution threshold $NPY = 0.077$ g N kg FCM^{-1}), optimal management settings use slightly lower stocking rates (0.9 to 1.4 LSU ha^{-1}, Fig. 6e) and substantially lower fertilizer input levels (25 kg N ha^{-1}, Fig. 6j) than EY_{pol}. In these simulations, production is not as high as in Y_{max} (11 kg FCM ha^{-1} d^{-1}, Fig 6o) but animals are still very productive (12 kg FCM LSU^{-1} d^{-1}). GHG emissions E_L are less than half of those for Y_{max} (33 to 46%) and NP_L very close to the reference run (1.7 kg N ha^{-1}).

4 Discussion

4.1 Effects of objectives

Optimal management settings – specifically fertilizer-livestock density combinations – depend fundamentally on the chosen objective. Simulated production systems substantially differ, strongly affecting both productivity and environmental impacts. Targeting maximum production (Y_{max}) is associated with substantial environmental impacts whereas both impact-intensity-minimizing objectives (EY_{min} and NPY_{min}) reduced both environmental impacts (E_L and NP_L) and livestock productivity considerably. These three objectives select relatively extreme management systems from the range of potential production systems. These systems range from highly productive with high environmental impacts to the exact opposite. While such edge cases are plausible for single-objective analyses, they lack practical relevance as no farmer would ignore productivity to minimize environmental impacts. The introduction of objectives that allow a certain resource intensity (EY_{pol} and NPY_{pol}) is based on the non-linearity of the relationship between resource use, productivity and impacts. This nonlinearity reveals that intermediate strategies – rather than single-objective-extremes – can achieve both high productivity and low environmental impacts. Since the permitted resource intensities selected here were quantiles from our simulations results, they are certainly not to be taken as recommendations. Maximizing productivity while adhering environmental constraints (as in EY_{pol} and NPY_{pol}) offers a practical framework for designing policy instruments that balance production goals with environmental impacts. Depending on the main goal of the intended intervention, the appropriate objective can be selected.

When targeting NP intensities, optimal management settings reduce NP_L even below the livestock- and fertilizer-free reference scenario, demonstrating that strategic grazing management can improve nitrogen cycling. The differences to the reference simulation can mostly be attributed to reduced leaching and only a minor part to volatilization. N_2O emissions originate

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partly from nitrification and predominantly from denitrification, an anoxic process stimulated in wet soils. Consequently, N_2O contributes minimally to total emissions in the dry steppes of the VLC region.

4.2 Limitations

Our assessment of management and production potentials in dry steppe regions has limitations. We used discrete levels of livestock density and fertilizer application rather than a continuous range. While simulating the full range would provide finer resolution of trade-offs between management intensity and environmental impacts, the general response to changes in fertilizer and livestock density show consistent patterns (Fig. 2). Additionally, uncertainties in climate scenarios (Nijsse et al., 2020; Zelinka et al., 2020) and model responses preclude precise identification of optimal management configurations. However, our discrete approach is appropriate for characterizing general tradeoffs and synergies, which is the main goal of this analysis.

An additional source of uncertainty is the dependence of soil carbon dynamics on land-use history. Historical land-use changes cause long-term soil carbon losses that substantially affect both E and E_L (Herzfeld et al., 2021). For the historical period, we have information about the extent of cropland and grassland but must rely on assumptions regarding grassland management intensity. Selecting management settings (Tab. 1) according to each objective produces gid-cell-specific time series in which optimal management varies temporally. To account for farmer reluctance to frequently change management strategies, we selected optimal strategies for 5-year periods rather than annually. Nevertheless, the selected time series of soil carbon dynamics may differ from simulations in which the chosen management settings are considered in a transient run.

While LPJmL captures complex interactions between grazing pressure and fertilizer inputs on grassland productivity, the implemented livestock production system (Heinke et al., 2023) captures solely the pasture-based part of commercial dairy production which typically requires substantial concentrate feed inputs and indoor housing. Although several large-scale biogeochemical models consider the effects of grassland biomass removal by grazing or mowing (Chang et al., 2013; Rolinski et al., 2018), it is still a challenge to include actual livestock production systems (Chang et al., 2017). The farm-level balance of crop and grass production for an optimal feed provision for livestock and the development of the herd is represented in numerous models but their ability to assess the corresponding environmental impacts is limited (van der Linden et al., 2020). However, their application on a larger spatial scale is mostly not intended and requires detailed information on the specific farm operations. In global assessment models (e.g. GLOBIOM, Havlík et al., 2014) which consider the specific conditions in livestock production systems such as crop-grass feed mixtures and indoor manure management, on the other hand, fixed productivity and emission values per LPS and animal type is defined (Herrero et al., 2013). Thus, the here simulated livestock productivity serves as a useful proxy and allows the consistent assessment of the dynamic environmental impacts of livestock grazing without modeling complex herd dynamics.

4.3 Land-use management intensity in VLC steppe regions

The study area in the VLC region plays a central role for food production in eastern Europe. A high degree of trade-offs especially for the pasture-based production leads to intensive interactions that require deliberate decisions. Our dynamic modeling approach evaluates management trade-offs by accounting for both changing environmental conditions and management decisions.

We focused on only two dimensions of the many options that farmers have for intensifying their production: livestock density and mineral fertilizer application. Results reveal nonlinear fertilizer responses, enabling the identification of management intensities that achieve substantial production while minimizing both resource intensities and environmental impacts. To highlight this principle of diminishing returns of fertilizer usage, we introduced constrained optimization objectives that maximize production within environmental thresholds, $\mathrm{EY_{pol}}$ and $\mathrm{NPY_{pol}}$. The chosen threshold values for resource intensity are necessarily arbitrary and site-specific, unsuitable for direct monitoring. Thresholds with practical relevancy depend on stakeholder values (how much productivity loss is acceptable for what environmental gain), regulatory systems and governance (e.g. how well are threshold breaches monitored and prosecuted) and also on processes currently not part of the LPJmL model (e.g., herd management, animal genetics, nitrogen inhibitors). Nevertheless, the model captures the strongly nonlinear relationship between production and environmental impacts. This nonlinearity provides an opportunity for climate-smart policy design that achieves substantial environmental benefits with minimal production losses. Small input adjustments may substantially reduce environmental impacts while barely affecting production. Sustainable management should therefore focus on input intensity ranges where impacts can be reduced substantially without compromising production.

Planning and implementation of such tailored management policies are hindered by substantial data gaps. Data on the actual grazed area and livestock density in the VLC region are limited. Only for the four northern Kazakh provinces (oblasts) belonging to the VLC region, current statistical records (see years 2022 to 2025 in Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan, 2025) allow some insights in the characterization of livestock systems. Here, moderate to low intensity systems with a high share of dairy cattle dominate in which roughage is the main feed ingredient (see section 2.1). Milk yield is reported with 15.3 to 20.0 $\mathrm{kg\ head^{-1}\ d^{-1}}$ for agricultural enterprises and 6.5 to 9.8 $\mathrm{kg\ head^{-1}\ d^{-1}}$ for smallholder farmers but the live weight of these animals are not directly comparable to the chosen LSU which represents an animal of 500 kg. The values of the simulated results may best fit to settings chosen under constraining objectives (especially with those under $\mathrm{NPY_{pol}}$). Apart from the statistical records, the livestock production and the associated land and resource requirements were assessed in this Kazakh region. Using a novel allocation model to balance animal numbers and their feed demand, Hankerson et al. (2019) derived low off-take rates and characterize the livestock production systems as low to moderate. They estimate that livestock production could be intensified and increased using more of the available pasture biomass.

This evaluation has to be embedded into substantial changes following the disintegration of the Soviet Union from 1990 to 2015 which reduced the usage of rangeland for livestock production (Baumann et al., 2011). Thus, grasslands were less intensely grazed and recovered (Baumann et al., 2020), cropland was abandoned and near-natural habitat functioning developed with increasing biodiversity benefits. In the same period, the role of fire management gained importance since both burnt area and fire frequency increased manifold within the 20^{st} century (Dara et al., 2020). Continued changes in agricultural extent and management intensity are expected to further increase available fuel load and intensify fire regimes (Dara et al., 2018).

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The changes ongoing since about 2000 with re-cultivation of formerly abandoned cropland (Petrick et al., 2013) and increasing livestock numbers (Kerven et al., 2016) cause both further abandonment and re-cultivation of cropland and grassland and open a window of opportunity to frame goals for climate-smart and sustainable agricultural development. Intensifying agricultural production is usually linked to biodiversity declines e.g. in Kazakhstan's near-natural grasslands (Kamp et al., 2016). Consequently, intensifying livestock production will affect the natural environment through multiple pathways beyond nitrogen pollution. Sustainable and climate-smart development of livestock systems in the VLC region may be realized with the restriction of animal numbers or densities but could focus on resource use intensities and the environmental impacts. Future studies could incorporate these dimensions using dynamic models that capture intra- and interannual variability in resource availability (Godde et al., 2020).

5 Conclusion

Grassland management in semi-arid steppe regions like the VLC area can be designed to comply with sustainability criteria. We demonstrate that combinations of management aspects allow for a broad range of system properties and simultaneously address environmental impacts and system productivity. Although we do not recommend climate-smart best-solution combinations, which require stakeholder decision making, we show that moderately less intensive systems reduce environmental impacts substantially without jeopardizing livestock productivity. The quantification of this nonlinear system behavior can help to inform decision makers to adjust management towards well-balanced interests in productivity and environmental protection or constraints given through regulatory systems.

Code availability. The source code of the model LPJmL version used in the study is available in the zenodo archive Schaphoff et al. (2026).

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Appendix A: Spatial and temporal distribution of grassland area in the VLC region

The large-scale conversion of steppe into cultivated areas during the Virgin Lands Campaign (VLC) was applied to 72 Mha from 1954 to 1963 of which 42 Mha were used as cropland. Grassland area decreased from 47.4 to 44.0 Mha by about 3.4 Mha during this period and remained relatively constant (standard deviation 1.1 Mha) until the end of the Soviet era (Fig. A1a). Then, cropland was abandoned and grassland coverage increased by about 12 Mha until 1999. Although the changes are substantial over time, they were concentrating on few areas and few moments in time. On average, 8% of the grid cells were not covered by grassland at all (yellow line in Fig. A1b). The share of grid cells with maximum 5% grassland dropped in 1990 from 41 to 33% and those with maximum 25% from 74 to 66% (lines for 0.05 and 0.25 in Fig. A1b). When the overall grassland area increased after 1990, it was increasing especially in grid cells with former shares of 15 to 65% in a monotonous way, which means that the net change was not a result of short-term decreasing and increasing grassland shares but a longer lasting land-use change. Grassland coverage around 1980 is highest in the southern part of the VLC area, especially in Kazakhstan, and only to limited extent in the western part (Fig. A1c) whereas the eastern VLC region has less than 10% grassland coverage. Comparing grassland area shares in 1980 (Fig. A1c) with those in 2010 (Fig. 1) does not show different patterns. Only the difference between both years (Fig. A1d) reveals few grid cells in Kazakhstan and in the south-western region in Russia with substantially increasing grassland area shares.

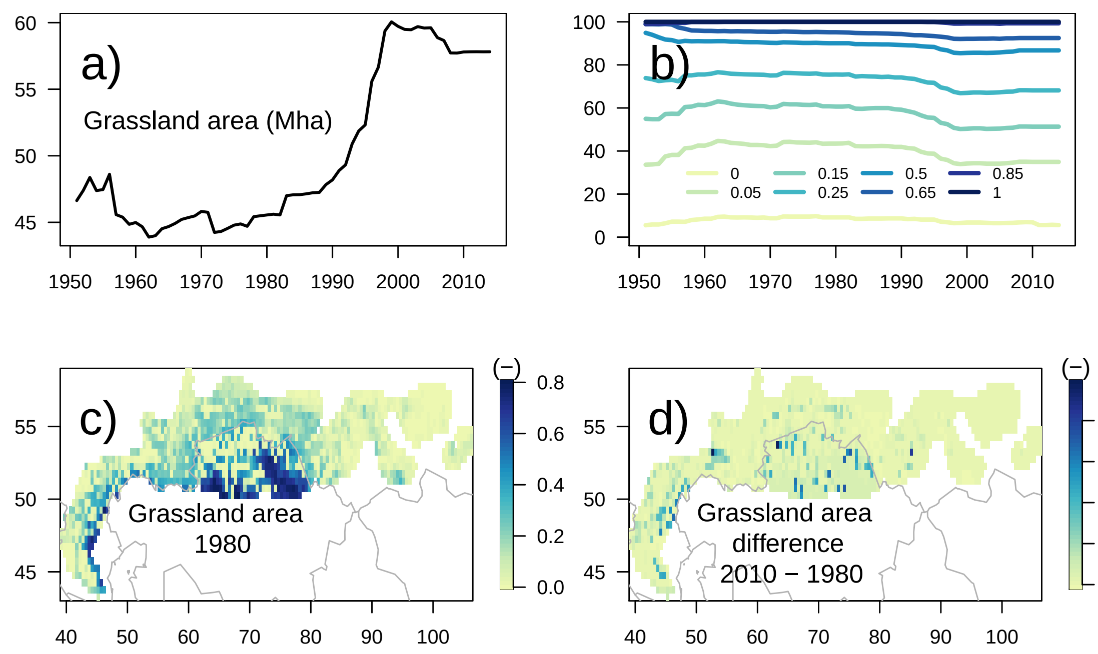

Figure A1. Time series of grassland area in the VLC region (a), and of the distribution of the grassland area fractions per grid cells in percent of the VLC area (b). Spatial distribution of grassland area in 1980 (c) and of the difference of grassland area fractions between the highest (2010) and lowest (1980) grassland coverage (d).

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Appendix B: Fertilizer response for other RCPs

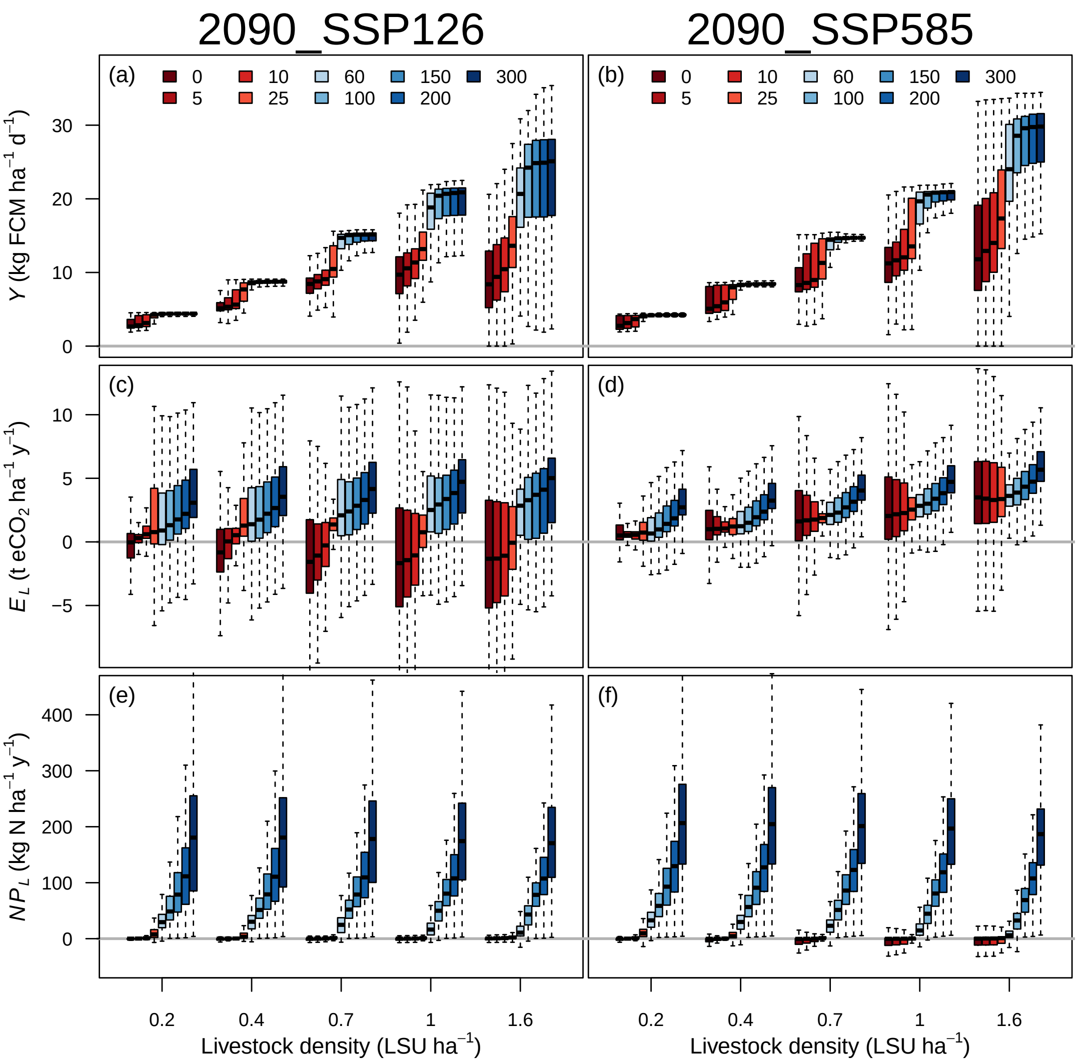

Figure B1. Annual responses to fertilizer application (colors; kg N ha^{-1}) per livestock density in the VLC region for 2900 under RCP 2.6 SSP1 (a, c, e) and RCP 8.5 SSP5 (b, d, f) for (a, b) livestock production (kg FCM ha^{-1} d^{-1}), (c, d) livestock-related GHG emissions E_L (t eCO$_2$ ha^{-1} y^{-1}) and (e, f) nitrogen pollution NP_L (kg N ha^{-1} y^{-1}). For each management setting, boxes enclose the 25% and 75% percentiles of all simulated grid cells in the study area, horizontal lines indicate median values and whiskers extend to 1.5 times the interquartile range.

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Appendix C: Non-linear response in single grid cells

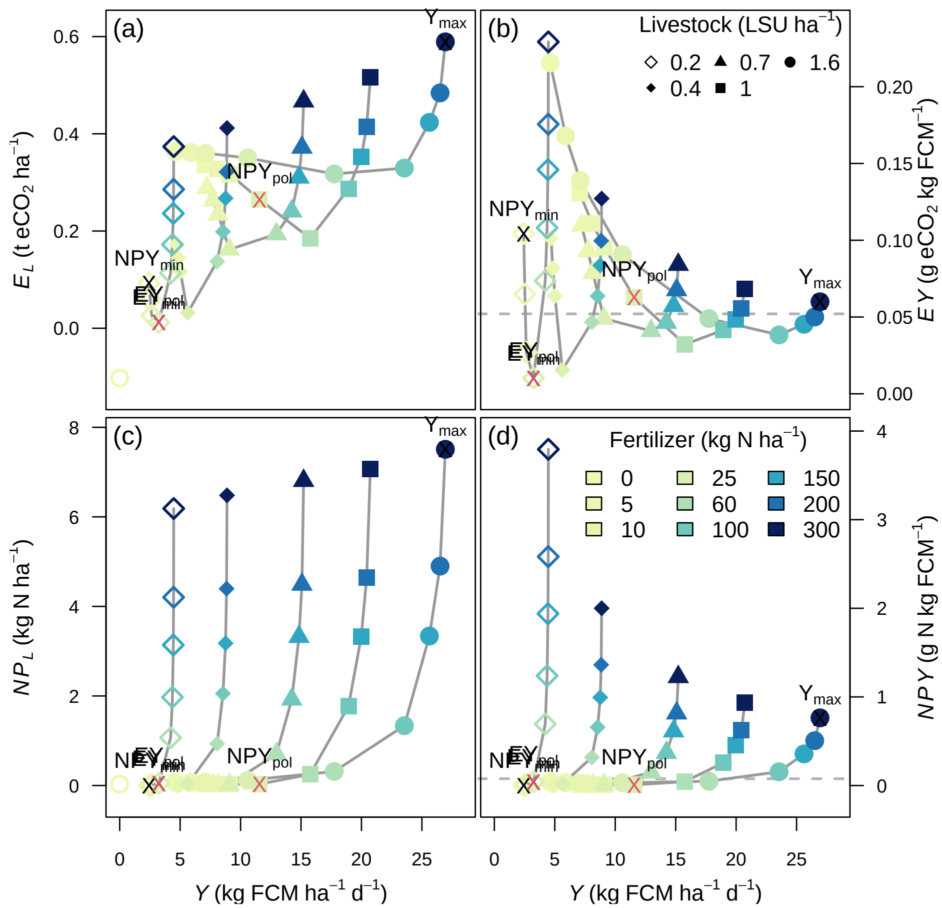

Figure C1. Livestock productivity Y for one grid cell (39.25° E, 47.25° N) versus (a) GHG emissions E_L, (b) GHG emission intensity EY, (c) nitrogen pollution NP_L and (d) nitrogen intensity NPY for all simulation management settings averaged for the period 2005 to 2014. Grey lines combine symbols for the same livestock density for better visibility. Results of objectives are given as crosses with labels above and dashed grey lines give threshold values for the policy objectives.

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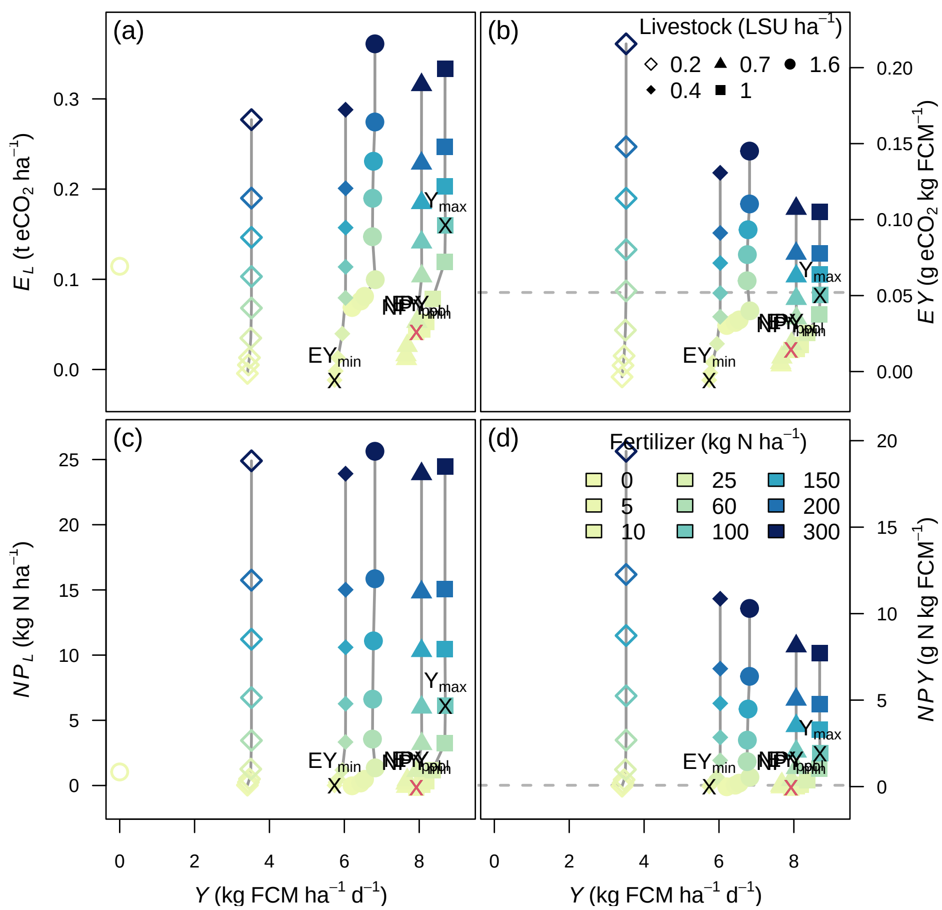

Figure C2. Livestock productivity Y for one grid cell (62.25° E, 50.75° N) versus (a) GHG emissions E_L, (b) GHG emission intensity EY, (c) nitrogen pollution NP_L and (d) nitrogen intensity NPY for all simulation management settings averaged for the period 2005 to 2014. Grey lines combine symbols for the same livestock density for better visibility. Results of objectives are given as crosses with labels above and dashed grey lines give threshold values for the policy objectives.

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Table C1. Average values for the GCM MRI-ESM2-1 for the period 2090-2100 for RCP 7.0 SSP 3 and fertilizer application rates of 0, 10 and 100 kg N ha^{-1} (first column). Variables shown are livestock density LSU, vegetation carbon VegC, manure carbon ManureC, livestock productivity Y, GHG emissions E, nitrogen pollution NP, annual soil carbon balance ΔC, soil carbon SoilC, litter carbon LitterC and the residence time of carbon in the soil RT. Livestock-related values would result from substracting values in the first row from the reference run.

N_{fert} $\frac{kg\ N}{ha}$	LSU $\frac{LSU}{ha}$	VegC $\frac{gC}{m^2}$	ManureC $\frac{gC}{m^2}$	Y $\frac{kg\ FCM}{ha\ d}$	E $\frac{t\ eCO_2}{ha}$	NP $\frac{kg\ N}{ha\ yr}$	ΔC $\frac{gC}{m^2\ yr}$	SoilC $\frac{kg\ C}{m^2}$	LitterC $\frac{kg\ C}{m^2}$	RT yr
0	0.0	899.1	0.0	0.0	0.06	0.69	-16.55	26.87	0.52	43.1
0	0.2	829.7	17.8	2.80	0.10	0.58	-11.82	27.50	0.47	43.7
0	0.4	723.9	35.4	5.17	0.15	0.50	-10.92	27.70	0.41	44.4
0	0.7	553.3	59.2	7.90	0.22	0.44	-11.25	27.63	0.33	45.0
0	1.0	418.7	77.6	9.29	0.28	0.48	-13.30	27.63	0.26	45.4
0	1.6	275.8	99.3	9.11	0.35	0.61	-14.31	27.71	0.20	46.1
10	0.2	846.3	17.7	3.18	0.12	0.87	-14.81	28.07	0.49	44.1
10	0.4	778.0	35.6	5.79	0.15	0.70	-9.12	28.71	0.45	44.8
10	0.7	628.8	60.9	8.99	0.22	0.57	-5.66	29.01	0.36	45.5
10	1.0	485.1	81.9	11.03	0.28	0.54	-5.44	29.09	0.29	46.1
10	1.6	317.1	108.5	11.52	0.36	0.70	-6.34	29.39	0.22	46.6
100	0.2	702.9	16.7	4.27	0.23	6.24	-22.18	26.19	0.46	43.8
100	0.4	656.9	33.1	8.37	0.28	6.04	-19.90	27.20	0.44	44.7
100	0.7	591.1	57.0	13.92	0.34	5.55	-15.62	28.66	0.40	46.0
100	1.0	528.2	79.6	18.44	0.40	5.03	-10.80	29.98	0.36	47.0
100	1.6	412.1	117.0	23.21	0.47	4.43	2.75	31.76	0.29	48.1

Table C2. Average values for the GCM MRI-ESM2-1 for the period 2095 for all objectives and RCPs (L: RCP 2.6 SSP 1, M: RCP 7.0 SSP 3, H: RCP 8.5 SSP 5). Variables shown are livestock density LSU (LSU ha^{-1}), fertilizer (kg N ha^{-1}), livestock productivity Y (kg FCM ha^{-1} d^{-1}), emissions E_L (t eCO$_2$ ha^{-1}), nitrogen pollution NP_L (kg N ha^{-1} y^{-1}), soil carbon (kg C m^{-2}) and soil nitrogen (kg N m^{-2}).

objective	Y_{max}			EY_{min}			EY_{pol}			NPY_{min}			NPY_{pol}		
RCP	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
LSU	1.5	1.6	1.6	0.6	0.6	0.6	1.1	1.3	1.3	0.4	0.5	0.6	1.1	1.4	1.5
N_{fert}	234.6	257.3	267.8	8.4	14.0	16.0	101.6	132.7	143.4	0.9	0.7	0.7	24.2	36.6	42.8
Y	20.7	25.9	26.3	5.5	8.9	8.5	16.3	20.9	21.1	5.1	6.9	7.8	13.5	18.9	19.9
E_L	4.8	6.1	5.6	0.4	0.5	0.0	2.8	3.8	3.0	0.9	1.0	0.9	2.5	4.0	3.2
NP_L	125.5	137.7	154.0	-0.4	-7.2	-5.1	44.4	59.5	71.7	-3.2	-12.6	-13.5	0.1	-1.7	2.7
soil C	13.0	14.9	15.7	8.2	9.5	8.3	19.6	20.3	19.4	5.5	7.8	8.5	15.7	19.5	20.1

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Appendix D: Figures for other RCPs

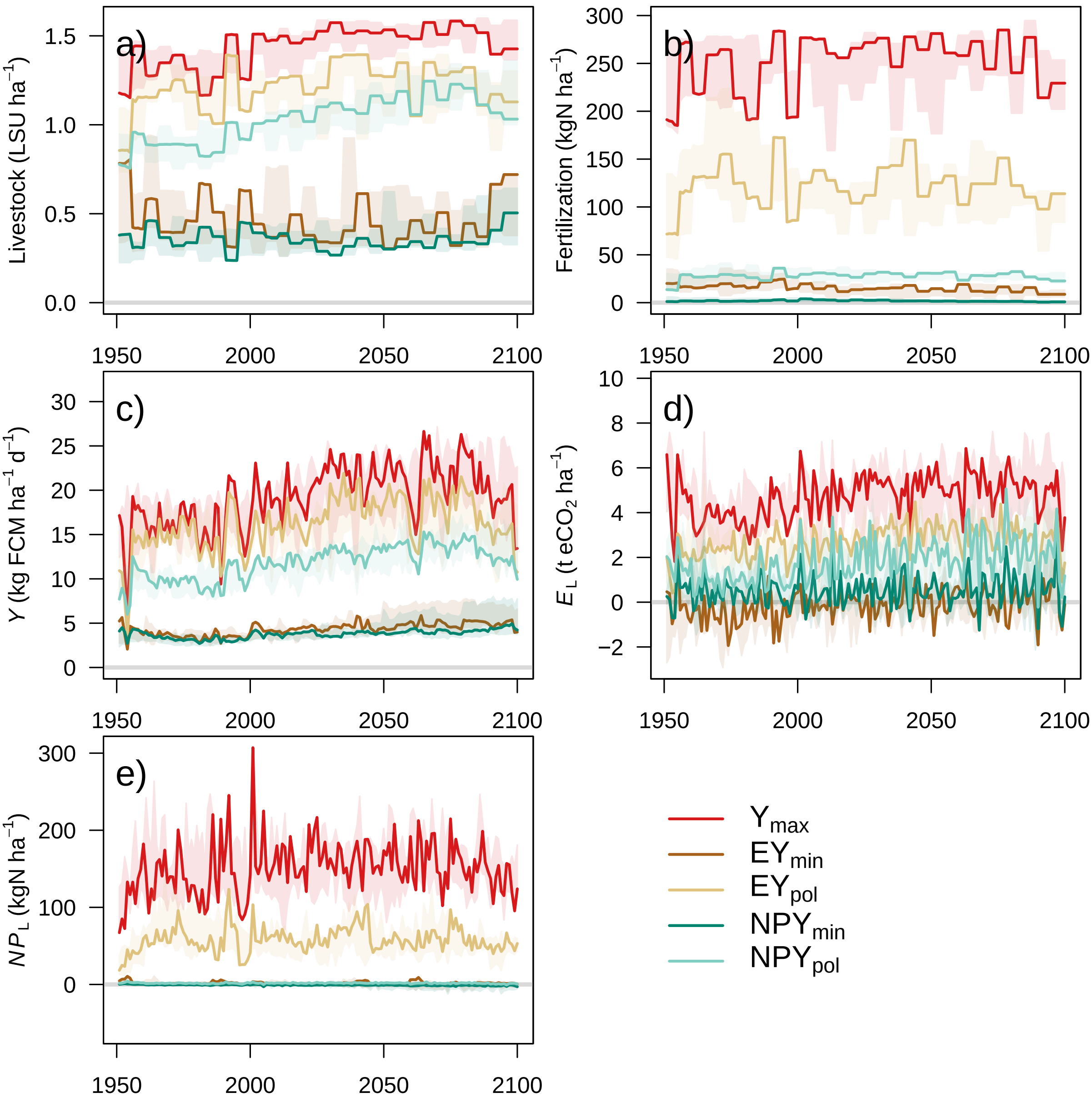

Figure D1. Same as Fig. 4 for simulation runs under RCP 2.6 SSP1.

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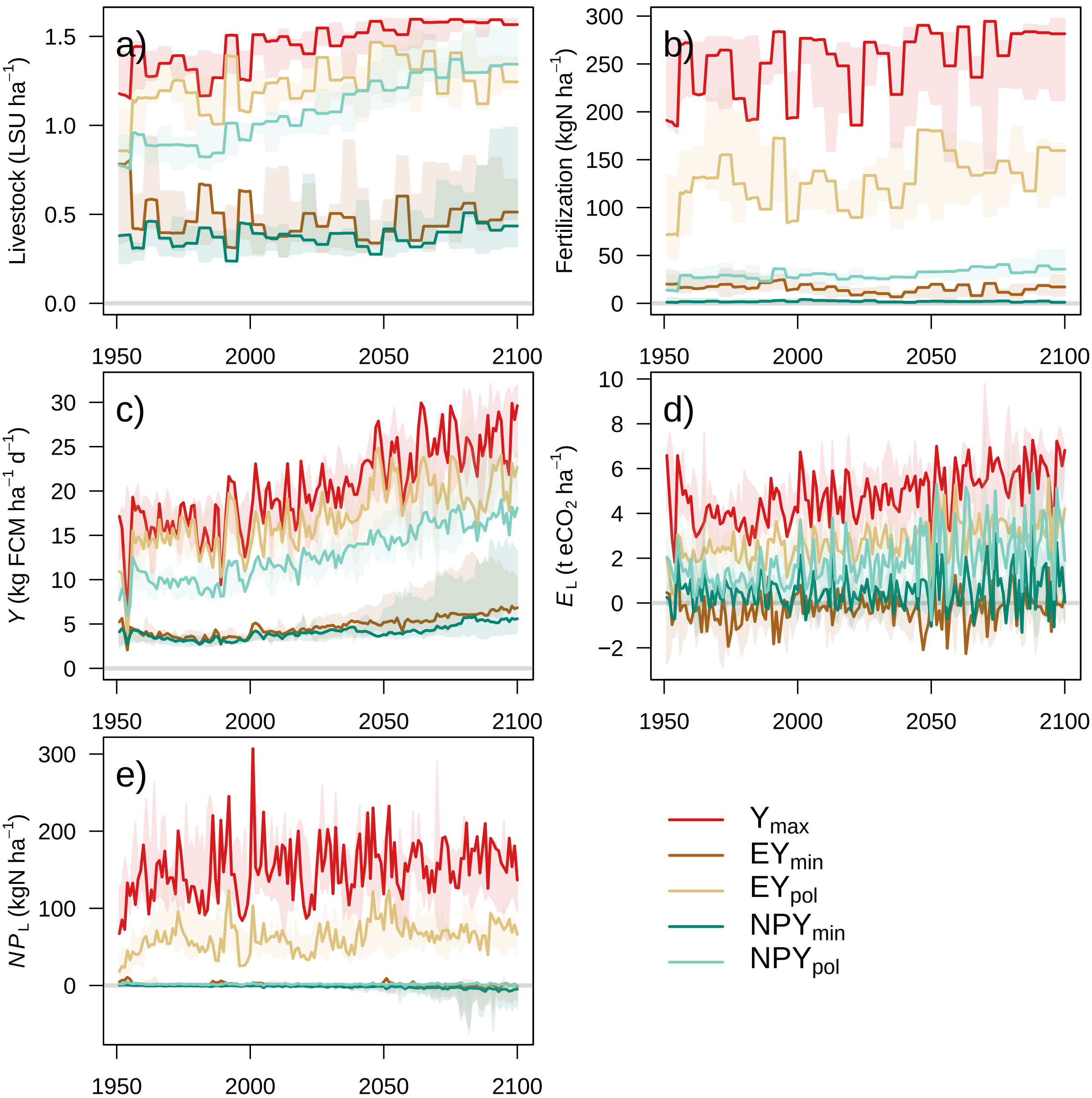

Figure D2. Same as Fig. 4 for simulation runs under RCP 8.5 SSP5.

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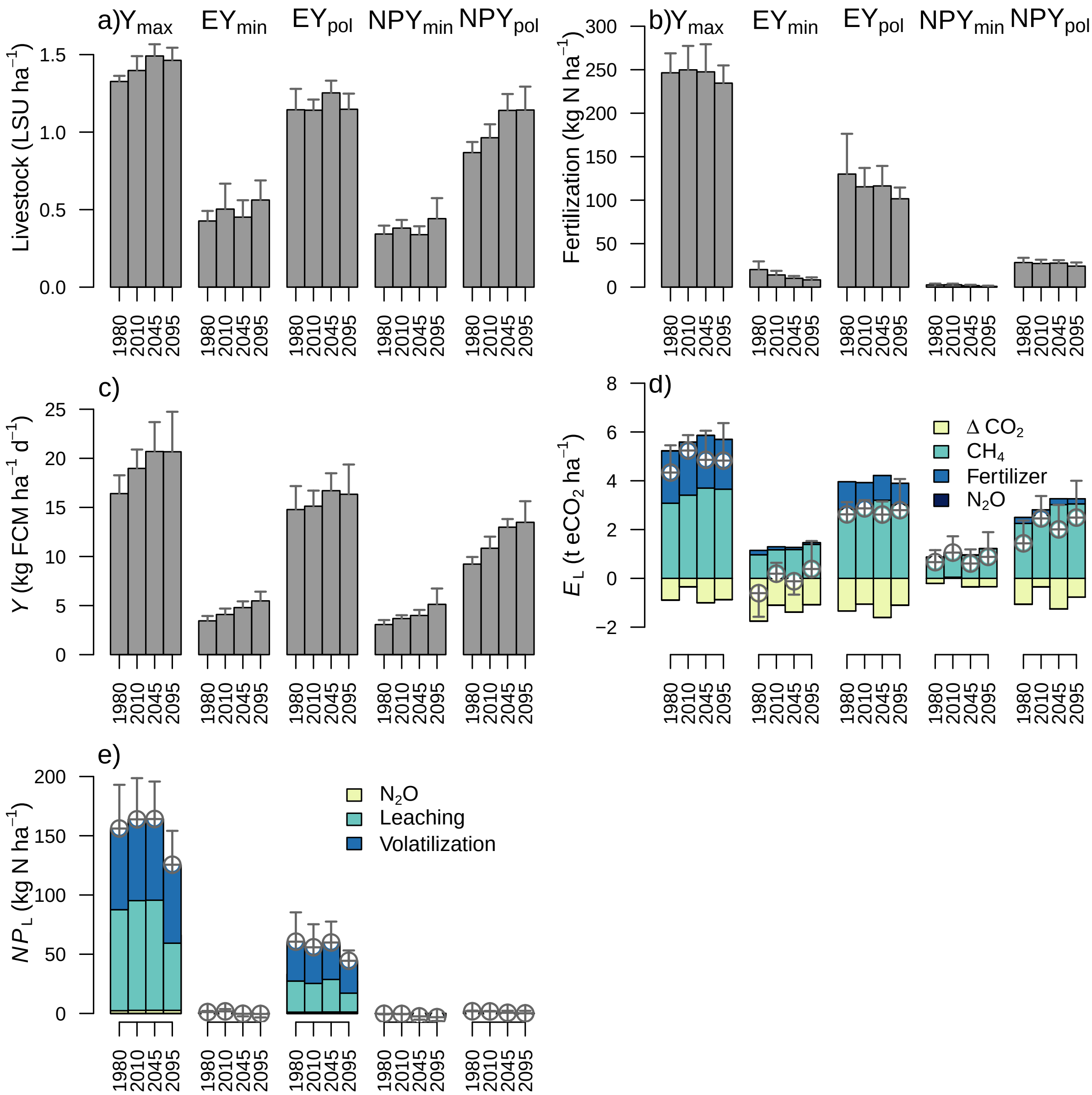

Figure D3. Average livestock-related values in the VLC region under RCP 2.6 SSP1 for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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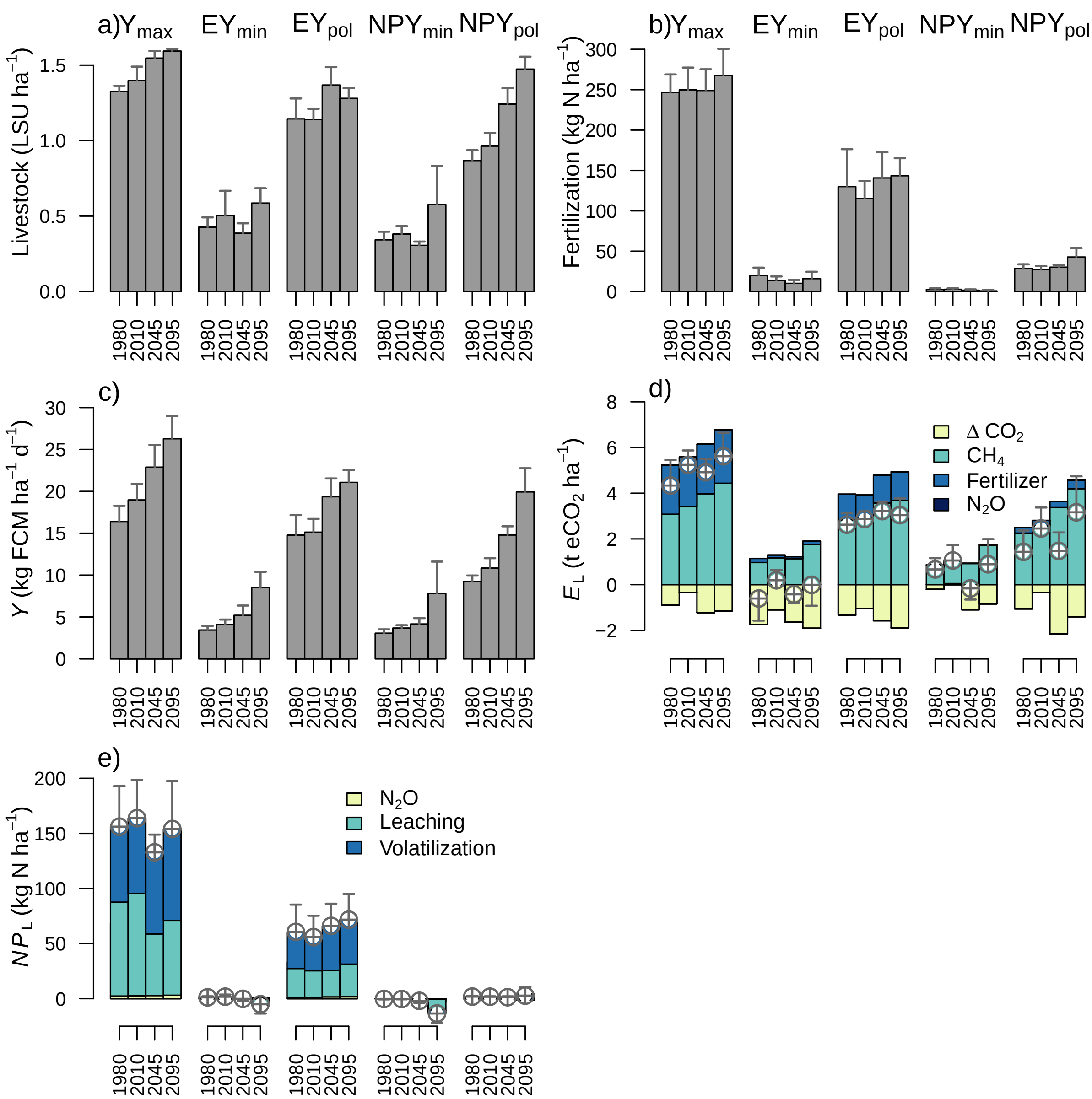

Figure D4. Average livestock-related values in the VLC region under RCP 8.5 SSP5 for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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565 **Appendix E: Variability of results due to climate input data**

The outcome of additional model runs using climate data from MRI-ESM2-1 and 4 other GCMs is illustrated by the average and the standard deviation of all results in Fig. 6 (section 2.3). GCM MRI-ESM2-0 was chosen for the analysis in the main text because the resulting patterns and order of magnitudes for all objectives and values correspond well to the average values across GCMs (Fig. E1). Deviations occur for the emissions E_L (Fig. E1 p to t) and nitrogen losses NP_L (Fig. E1 u to y) but to 570 a minor extent.

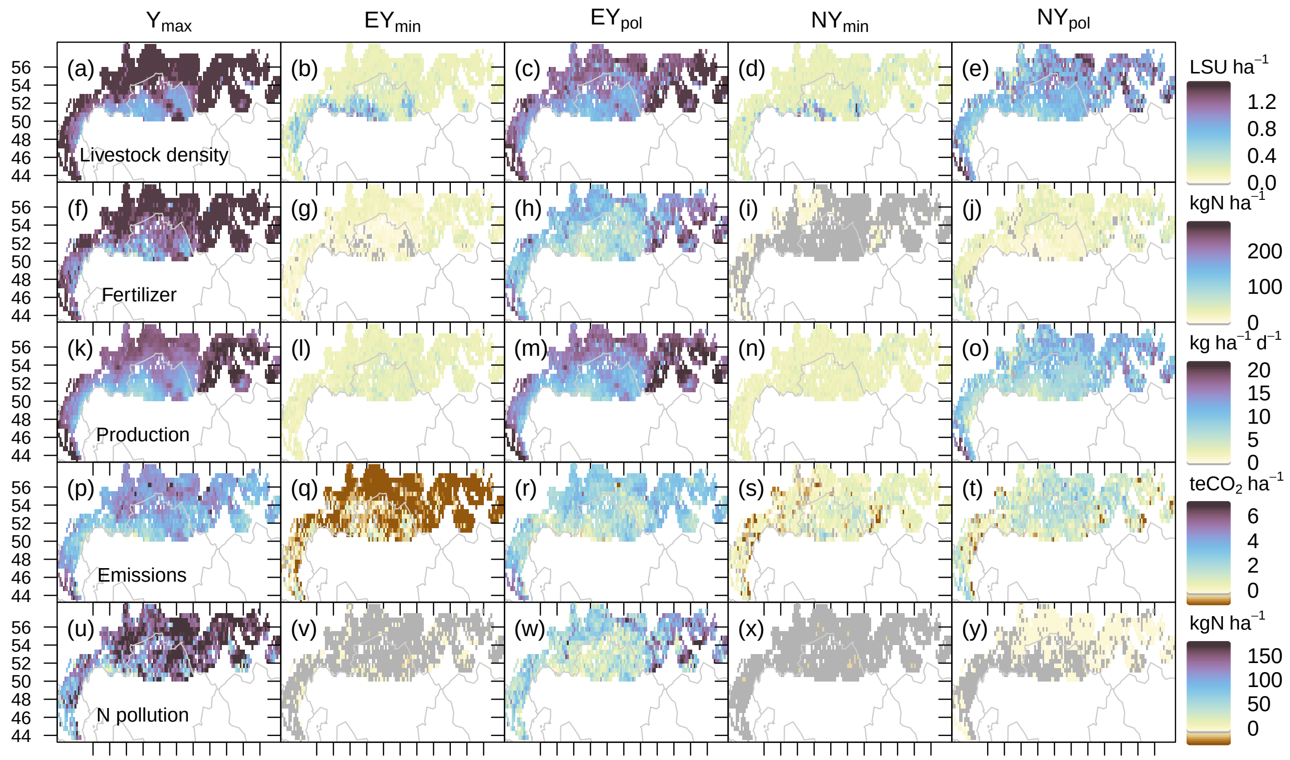

Figure E1. Averages over all GCMs for the same objectives and variables as in Fig. 6.

The results for other GCM runs deviate in different aspects for the single objectives (Fig.E2). For $\mathrm{Y_{max}}$, all variables show higher standard deviations in the regions with low average values, e.g. in the Kazakh region for the livestock density and the nitrogen pollution. In contrast, standard deviations are high in areas with high values for $\mathrm{EY_{pol}}$, e.g. in the south-eastern part for the livestock densities or in the center region for E_L. Highest deviations are determined for the fertilizer application in the 575 northern region of about 90 $\mathrm{kg\ N\ ha^{-1}}$ for fertilizer application and of 60 $\mathrm{g\ N\ m^{-2}}$ for NP_L.

Appendix F: Figures with and without livestock caused impacts

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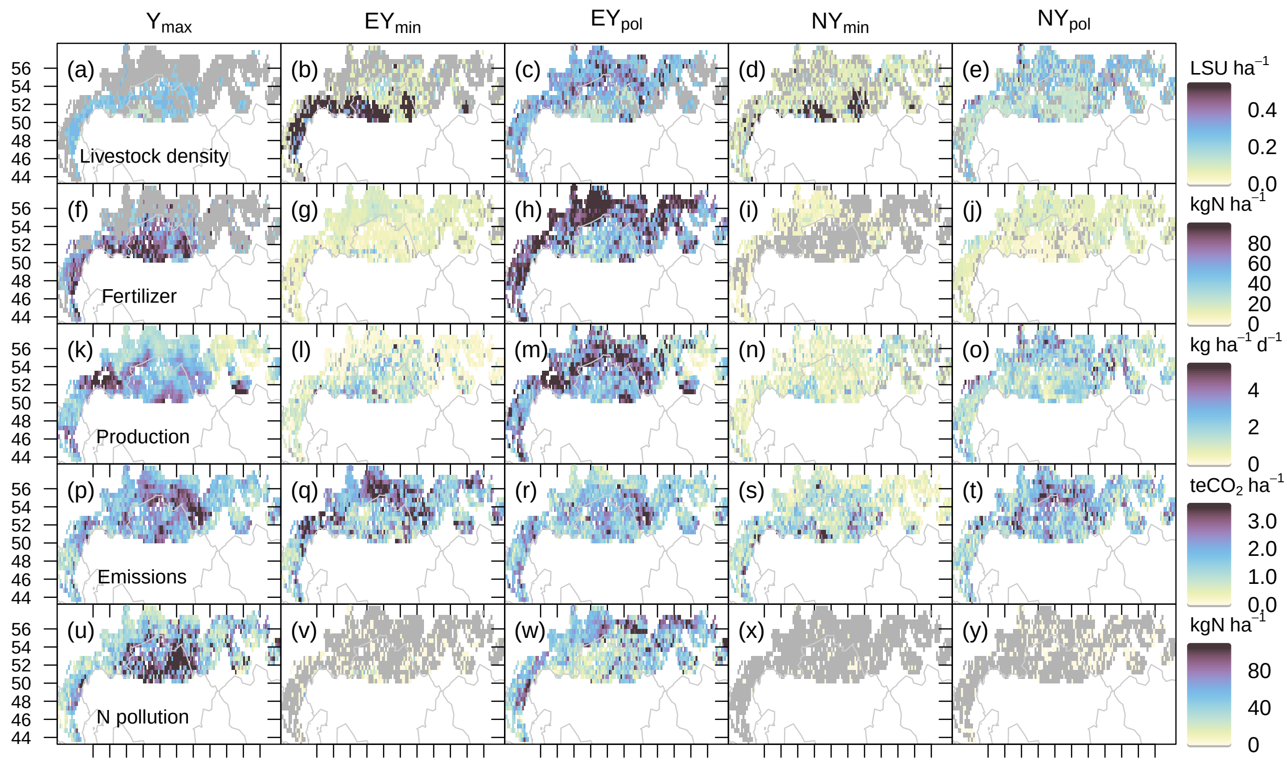

Figure E2. Standard deviation over all GCMs for the same objectives and variables as in Fig. 6.

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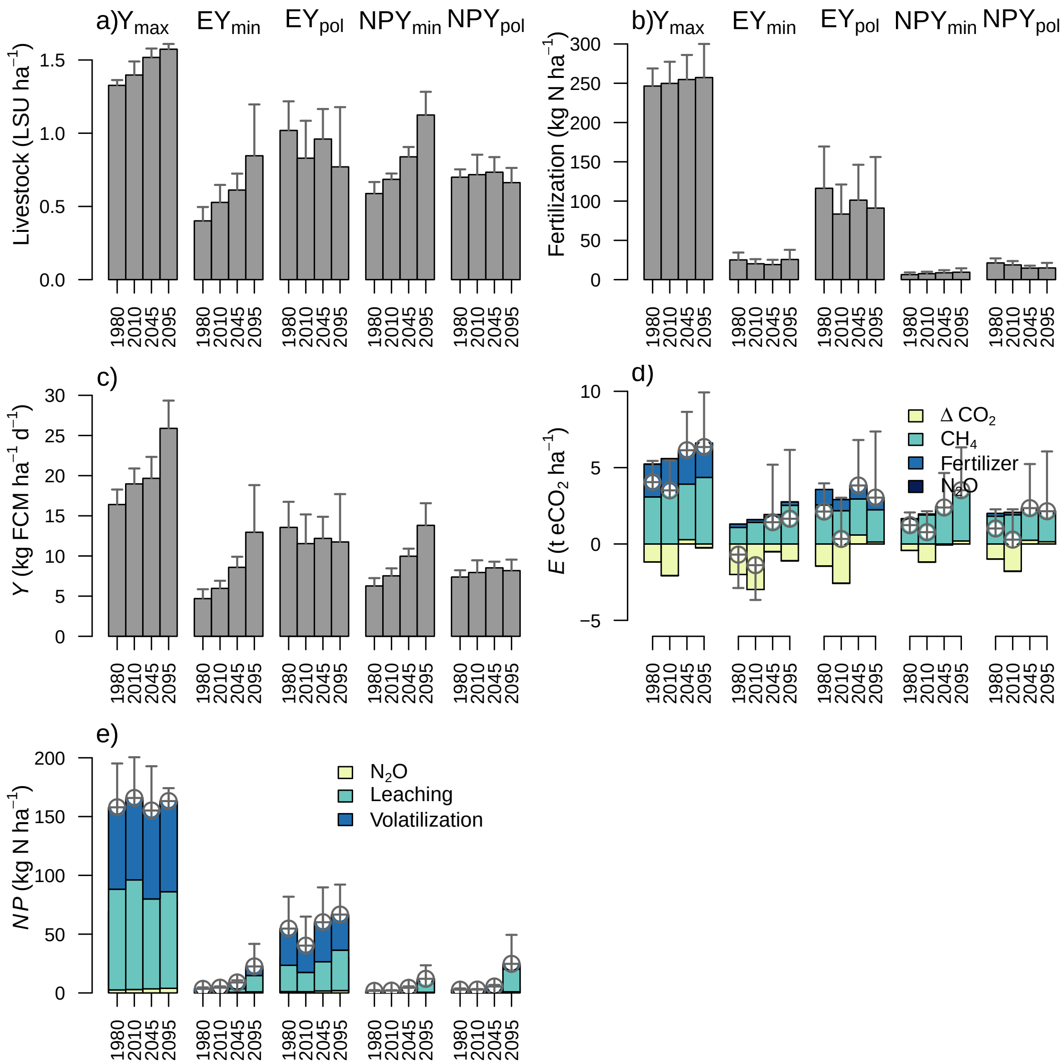

Figure F1. Average total values in the VLC region under RCP 7.0 SSP3 for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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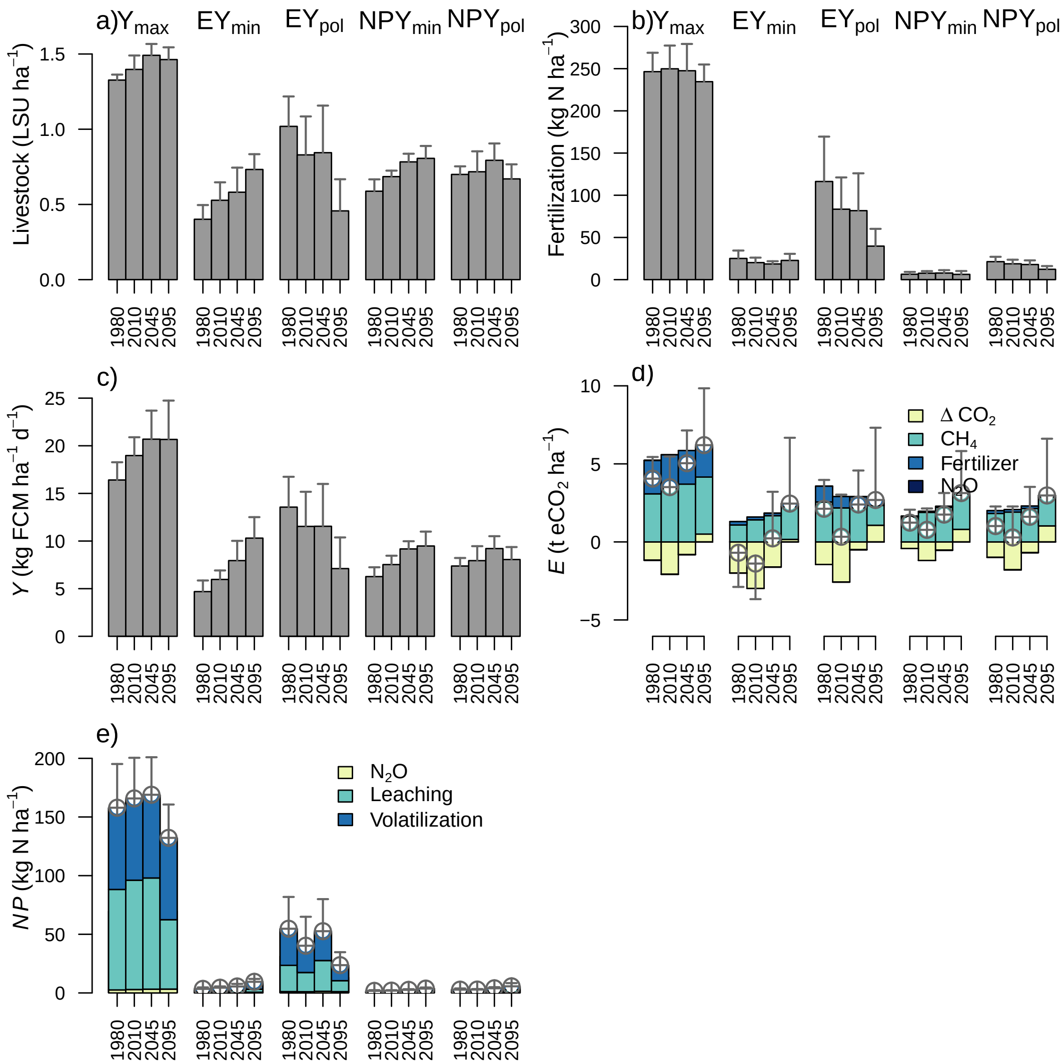

Figure F2. Average total values in the VLC region under RCP 2.6 SSP1 for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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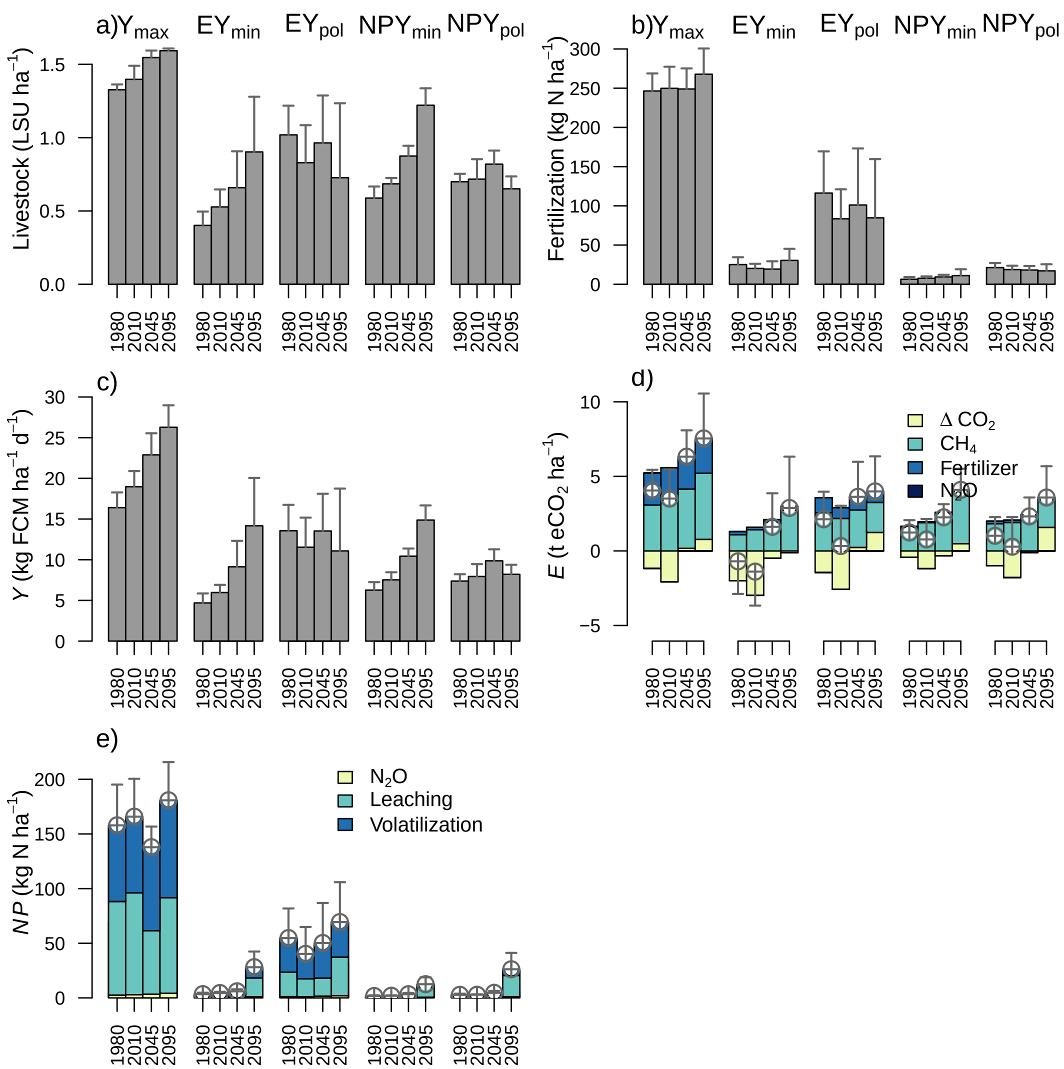

Figure F3. Average total values in the VLC region under RCP 8.5 SSP5 for all objectives and four periods (1980: 1976-1984; 2010: 2006-2014; 2045: 2041-2049; 2095: 2091-2099). Shown are the best-performing livestock densities (a), the fertilization levels (b), as well as the resulting livestock productivity (c), GHG emissions E_L (d), and nitrogen pollution NP_L (e). Contributions of individual GHG emission to E_L and NP_L are shown and net effects denoted by the symbol. N_2O emissions in panels d and e are non-zero, but too small to be visible.

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Author contributions. SR and CM designed the study and SR performed scenario runs and the analysis. All authors contributed to writing the manuscript.

Competing interests. The authors have no competing interests.

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