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Effects of alternative crop-livestock management scenarios on selected ecosystem services in smallholder farming - a landscape perspective

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Abstract.
Smallholder farming systems in southern Africa are characterized by low-input management and integrated livestock and crop production. Low yields and dry-season feed shortages are common. To meet growing food demands, sustainable intensification (SI) of these systems is an important policy goal. While mixed crop-livestock farming may offer greater productivity, it implies trade-offs between feed supply, soil nutrient replenishment, soil carbon accumulation and other ecosystem functions and services. Such settings require a detailed systems understanding to assess the performance of prevalent management practices and identify potential SI strategies. Models can evaluate different management scenarios on extensive spatio-temporal scales and help identify suitable management strategies. Here, we linked the process-based models APSIM for cropland and aDGVM2 for rangeland to investigate the effects of (i) current management practices, (ii) a SI scenario for crop production, and (iii) a scenario with separated rangeland and cropland management in two representative villages of the Limpopo province, South Africa, for the period 2000-2010. Village surveys informed the models of farming practices, livelihood conditions, and environmental circumstances. We found that modest SI measures (manure application, small fertilizer quantities, weeding, crop rotation) led to moderate yield increases but could cause increased water limitation effects in dry years. SI effects therefore strongly varied between years. Dry-season crop residue grazing substantially reduced feed deficits, but could not compensate severe feed deficits during the transition period from dry to wet season. Targeted irrigation or measures to improve water retention and soil water holding capacity may enhance SI efforts. Off-field residue feeding during the dry-to-wet season transition could further reduce feed deficits and reduce grazing pressure on rangeland during the early growing season. We argue that integrative modeling frameworks are needed to evaluate landscape-level interactions between ecosystem components, evaluate

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the climate resilience of landscape-level ecosystem services, and identify effective mitigation and adaptation strategies.

Key words: smallholder farming, mixed crop-livestock farming, Southern Africa, ASPIM, aDGVM2, vegetation modeling, dry-season feed gap, sustainable intensification

Dedicated to the memory of our esteemed colleague Marian Koch

1 Introduction

Smallholder farms occupy approximately 62% of Africa's farmland area. Family-driven labor generates household income and food security (FAO, 2014) and heavily relies on natural ecosystem functions and services (ESF and ESS). Low income and education levels, poor access to markets and credits, lack of technology, and strong dependence on external support from governments and NGOs in form of safety nets, advisory support, off-farm income such as pensions, or donations, are challenges that endanger food security, welfare, and well-being of smallholders (FAO, 2015). These obstacles impede the capacity to mitigate and adapt to climate change (Harvey et al., 2013). Livestock husbandry and subsistence cropping characterize smallholder farming in Africa (Thornton and Herrero, 2015; Descheemaeker et al., 2016). Livestock provides milk, meat, and leather, conveys prestige, and contributes to economic diversification. Livestock often feeds on crop residues during the dry period, which allows rangeland resting, accelerates nutrient recycling, and links both land-use types. Although integrated crop-livestock farms may offer greater farming efficiency and sustainability (Sumberg, 2003; Herrero et al., 2009; Tarawali et al., 2011) they often lead to various trade-offs (Herrero et al., 2009; Erenstein, 2002). Harvest residues as fodder reduce feed gaps whereas leaving them on-field allows for nutrient replenishment and enhances soil fertility (Castellanos-Navarrete et al., 2014; Valbuena et al., 2012). However, freshly excreted nutrients from livestock are not used during dry-season fallow and considerable nutrient losses can occur (Hack-ten Broeke et al., 1996).

Climatic variability creates additional challenges. Southern Africa experiences high inter-annual rainfall variability due to the El Niño–Southern Oscillation phenomenon (Conway et al., 2015). Increased stocking density during high-rainfall years results in forage shortages in subsequent dry years. Over-stocking without feed supplementation then results in severe pressure on the drought-afflicted vegetation and leads to animal malnutrition, increased livestock mortality, economic losses, and threats to ESS provided by rangelands (Müller et al., 2015). Overgrazing may lead to rangeland degradation, species loss, reduced carbon transfer to soils, and habitat deterioration. Higher bare ground fractions increase run-off, soil erosion, and evaporation.

Focusing on the multi-functionality and complex interactions of mixed cropland-rangeland systems is necessary to evaluate the performance of prevalent cropping and livestock husbandry practices and identify possible site-specific sustainable intensi-

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fication strategies (Giller et al., 2006; Rusinamhodzi et al., 2011). Observational assessments of different management options requires numerous field experiments, which are often limited by time and resource constraints. In contrast, models can systematically explore different management scenarios on various spatiotemporal scales and help identify suitable management strategies once they have been evaluated satisfactorily (Kersebaum et al., 2015). Crop simulation models (CSMs) simulate the effects of different management strategies on biomass, yield, water use and nutrient uptake for numerous combinations of genotype and environment interactions (see, e.g., Rötter and Van Keulen, 1997; Whitbread et al., 2010). Livestock models that simulate animal productivity (meat, milk) depending on age, gender, and status (e.g., juvenile, pregnant, or lactating, see van de Ven et al., 2003) can integrate the output of such CSMs. For example, Descheemaeker et al. (2018) used the crop model APSIM (Holzworth et al., 2014) and the livestock model Livsim (Rufino et al., 2015) within the AgMIP framework (Rosenzweig et al., 2013) to investigate climate change effects on forage availability and livestock and crop productivity. Dynamic vegetation models (DVMs) simulate natural vegetation dynamics, carbon sequestration, energy and water fluxes, and biomass production in response to environmental drivers and disturbances. Recent developments increasingly focused on anthropogenic influences and aim to include management. For example, the aDGVM, a DVM developed for African savanna ecosystems (Scheiter and Higgins, 2009), has been expanded to simulate fuelwood harvesting and grazing to determine how climate change influences the economic value of ESS in southern African rangelands (Scheiter et al., 2019). New routines in the trait-based aDGVM2 allow for an improved representation of grass-layer diversity and simulation of selective grazing (Pfeiffer et al., 2019).

While assessments of ESF in crop-livestock systems are crucial for smallholder farming communities in sub-Saharan Africa (Descheemaeker et al., 2016; Waha et al., 2018),CSMs and DVMs commonly consider cropland and rangeland independently. While such applications improve the individual system understanding, only a coupled framework that combines CSMs and DVMs can capture landscape-scale interactions. In this study, we linked APSIM with aDGVM2, two models that are both well-tested for southern Africa (Hoffmann et al., 2018a, b, 2020; Pfeiffer et al., 2019).We linked simulations of cropland and rangeland dynamics for two villages in South Africa's Limpopo province to test the impacts of different management scenarios on landscape-scale ESS: status quo, minimum sustainable intensification, separated vs. combined cropland-rangeland management. The APSIM model delivered results on yield, biomass productivity, carbon sequestration and water use. We then used this output to compare feed demand with simulated harvest residues to determine whether cropland can cover the feed demand during dry seasons. The aDGVM2 simulated rangeland vegetation dynamics and biomass consumption during periods when livestock had no cropland access. The aDGVM2 output showed whether or not rangeland could satisfy animal demand during those periods. Moreover, seasonal and interannual high-risk times for feed deficits were determined. Such an integrative analysis combines the strengths of crop and rangeland models and is the first attempt in this form. We asked the following questions:

1. Do village-specific sustainable intensification measures improve ecosystem services and functions compared to status quo land use practice, and which functions and services are affected?
2. Do feed gaps occur and are there village-specific differences?
3. Can joint management of cropland and rangeland reduce or eliminate feed gaps?

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4. Can integrated modeling of cropland and rangeland identify management strategies that result in a sustained provision of landscape-level ecosystem functions and services?

2 Material and Methods

2.1 Study region

South Africa's Limpopo province has a high share of smallholder farmers who often experience food insecurity. Maize is a staple crop, accompanied by legumes including peanut, bambara nut, cowpea, and some tubers. Cropping systems are low-input with limited or no fertilizer application, and farmers typically broadcast seeds. Climate conditions range from a warm desert climate in the West to a warm semi-arid to humid climate in the East (Engelbrecht and Engelbrecht, 2016). Ca. 80% of annual precipitation falls during the cropping season from October to April/May, followed by a May-October dry season. We selected two villages representing the climate extremes for arable farming in the province: Gabaza and Selwana (802 mm MAP and 585 mm MAP, respectively; 2000-2010 period, (Ruane et al., 2015)). Average daily maximum temperatures in January are 30.6 °C and 32.4 °C, and 24.3 °C and 25.9 °C in July for Gabaza and Selwana, respectively (Tab. 1). Both villages are part of research projects (SALLnet, Rötter et al., 2021, https://www.uni-goettingen.de/de/592566.html) and under survey since 2013 (Tab. 1).

2.2 Current smallholder farming practices versus a minimum sustainable intensification scenario

Farmers in Limpopo have adapted their crop-livestock practices to the strong climatic seasonality. Cattle graze on the communal rangeland during the cropping season. After crop harvest, when rangeland provides little feed, livestock frequently consumes the remaining crop residues on-site (Bennett et al., 2009). Sometimes herders destroy fences to give cattle access to fields, potentially causing conflicts with crop farmers. We characterized village-specific cropping patterns based on a survey and ground-truthing campaign conducted in April and May 2019 and on background information based on working with smallholders in the region for >20 years. Table 1 summarizes the cropping patterns.

More than 90% of the farmers individually cultivate <1 ha and typically receive land usage rights from the community (Permission to Occupy, PTO). Maize is the prevailing regional staple (Tab. 1) complemented by legumes, e.g., peanuts and cowpea. Smallholders often recycle maize seeds from the previous harvest. Seeds are broadcasted, planting density is low and frequently ranges between 1-5 plants/m^2. While mineral fertilizers are uncommon, cattle feeding on harvest residues accelerates nutrient cycling and concentrates nutrients in dropped manure. Weeds are widespread and sporadically hand-weeded. Farmers do not use agricultural chemicals or machinery. Maize yields are often <1 t/ha, with 2-3 t/ha in good years (manure input and regular weeding). We termed this Status Quo of cropland cultivation as the "SQ-scenario".

For the minimum sustainable intensification scenario (minimum SI-scenario), we prescribed 50 kg ha^{-1} yr^{-1} of N-fertilizer and manure application at sowing to increase nutrient supply, but did not consider any phosphorus or potassium applications. Additionally, we implemented weeding during the crop growth period and crop rotation to avoid soil exhaustion. Cattle had

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Table 1. Site characteristics of the two selected study villages and cropland usage (% of cropland area) for the most common crop types according to village surveys conducted in 2019.

	Unit	Gabaza	Selwana
Coordinates	lat, lon	23°59'25" S, 30°19'42" E	23°41'59" S 30°57'03" E
Elevation	m a.s.l.	676	372
Average annual rainfall	mm	802	585
Coeff. of variation for annual precip.		0.39	0.44
Avg. daily mean temp. January	°C	24.6 ± 2.2	26.3 ± 2.3
Avg. daily mean temp. July	°C	15.6 ± 2.3	17.2 ± 2.3
Avg. daily max. temp. January	°C	30.6 ± 3.3	32.4 ± 3.6
Avg. daily max. temp. July	°C	24.3 ± 3.5	25.9 ± 3.5
Avg. daily min. temp. January	°C	19.3 ± 1.9	20.9 ± 2.0
Avg. daily min. temp. July	°C	8.7 ± 1.9	10.4 ± 1.9
Soil texture		Sandy clay loam	Sandy loam
Main ethnic group		Tsonga	Pedi
No. of inhabitants		2413	5263
Avg. annual household income	ZAR	54627	75585
Formal education aged 20+	%	86.7	80.1
Water access on homestead	%	1.5	9.6
Distance from paved road	km	<5	5-10
Cropland allocation to maize	%	28.5	41
Cropland allocation to cowpea	%	5.5	9
Cropland allocation to bambara	%	15	9
Cropland allocation to peanut	%	15.5	9
Cropland allocation to pumpkin	%	15	8
Livestock units		90	87.4
Rangeland area size	ha	1431	2128
Rangeland woodland/grassland ratio		71/29	55/45

access to the cropland in the dry season (post-harvest) in both SQ and SI scenarios. This represents a low level of intensification but yet an improvement of the current Status Quo. We deem it realistic that our assumptions for sustainable intensification are feasible for smallholder farmers in the target villages even under current resource constraints, as farmers interviewed in surveys indicated that similar efforts are already made in neighboring villages.

2.3 Cattle and rangeland management according to village surveys

During the 2019 survey, local guides approached herders to assess cattle number, age, gender, and breed to establish village-specific feed demand and rangeland usage habits. At Selwana, the rangeland consisted of well-fenced 'herder camps' where herders and cattle lived semi-permanently and animals stay on the rangeland over night. In contrast, herders in Gabaza graze animals during the daytime and return to the homestead at night to reduce the risk of theft. In Gabaza, brief interviews with herders were conducted in the morning before they sent livestock to the rangeland, which also allowed for the visual assessment of the herds. As tracking the herds with GPS collars was not possible, interviewers asked herders to delineate grazing areas on maps. For the parameterization of the rangeland simulations, we determined the daily village-level dry matter demand based on the livestock units, assuming a daily dry matter demand of 12.5 kg/LU. For APSIM simulations, we additionally calculated the monthly energy and protein demand of herds based on the surveys to estimate nutrition-based input of manure to cropland. For this, we parameterized dry matter content, metabolizable energy, crude protein and dry matter digestibility using the values established by Descheemaeker et al. (2018, see their Table 1).

2.4 Crop growth simulation using APSIM

We simulated crop growth and development using the Agricultural Production System sIMulator (APSIM v7.9, https://www.apsim.info), which is partly based on early modeling work conducted in Kenya (Keating et al., 2003). Crop growth and development in APSIM are calculated on a daily time step and are affected by temperature, radiation, and water and nutrient supply. APSIM also calculates the dynamics of soil water, nitrogen, phosphorus on a daily basis. Model outputs include cardinal physiological stages such as duration of flowering and physiological maturity, total above- and belowground biomass, yield, water balance components such as evapotranspiration and soil moisture in different depths of the root zone, nitrogen uptake, nitrate leaching, etc. (Probert et al., 1998; Wang et al., 2014; Whitbread et al., 2017). For a general overview of APSIM applications in Africa, see Whitbread et al. (2010). For information on APSIM performance regarding different crops and functional aspects, see the studies in Table S1.

2.5 APSIM simulation setup

We ran APSIM for the period 1998-10-01 to 2010-10-01 using AgMERRA climate data (Ruane et al., 2015). Sowing took place in a time window between November and December once cumulative rainfall reached 20 mm within a five-day period. Crops were harvest in April/May (see Fig. 1e,f and Fig. 2). We simulated soil water, soil organic carbon (SOC), N, and P continuously between cropping cycles. SOC was halved every 30 cm (see Dagliesh et al., 2016) and simulated to a soil depth of 180 cm, with constant soil texture below the root zone, based on SOC starting values measured during a 2015 field campaign. Simulated crops included maize (sc501), peanut (kangwana), and cowpea (banjo), the most common local types of each crop (see, e.g., Hoffmann et al., 2018b; Rapholo et al., 2019; Hoffmann et al., 2020). We used a generic summer grass and a winter dicot to simulate weeds. Weeds in the SI-scenario were removed at a weed biomass threshold of 2 t/ha but at a maximum of 30 days (up to three times during the cropping season) to emulate findings from the ground-truthing campaign (see section 2.2).

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We simulated two scenarios: i) the average farmers' practice observed in the villages (i.e., "Status Quo", termed SQ-scenario) and ii) a minimum sustainable intensification scenario ("SI-scenario"), according to the specifications defined in section 2.2.

2.6 Modeling rangeland dynamics

The aDGVM2 simulates the daily growth and state of individual plants on representative 1-ha stands (Scheiter et al., 2013; Langan et al., 2017). Trait sets describe each individual's growth form (grass, tree, shrub, perennial or annual grass), leaf characteristics (specific leaf area, photosynthetic pathway), carbon allocation to plant compartments, plant architecture (roots, crown shape), response to fire, reproduction, and mortality. Plant performance emerges from trait characteristics and environmental filtering (Scheiter et al., 2013; Langan et al., 2017; Pfeiffer et al., 2019). The model has been specifically developed and tested for conditions in southern Africa (Pfeiffer et al., 2019). To represent grass functional diversity and grazing impacts, the model simulates annual and perennial grasses and accounts for preferential grazing (see model description in Pfeiffer et al., 2019).

2.6.1 aDGVM2 simulation setup

The aDGVM2 required animal presence times, the number of livestock units (LUs), and the dry matter demand per LU to determine daily hectare-based biomass removal. We assumed that animals move from cropland to rangeland two weeks before planting and return two weeks after the completion of the crop harvest to feed on crop residues during the dry season. SI or SQ crop management did not influence the timing of rangeland grazing simulations, because the timing of sowing and harvest maximum varied by a few days.

We simulated three different scenarios: 1) Rangeland-only scenario (RO): animals exclusively graze on rangeland; 2) Rangeland-cropland scenario (RC): animals on rangeland during the cropping season, animals on cropland during the dry season; 3) Control scenario (CO): no cattle presence, very low-intensity background grazing on random days (frequency equal to mean annual frequency of RC-scenario, animal density equal to 25% of the mean animal density of the RC-scenario) following the scheme described in Pfeiffer et al. (2019) to ensure the development of a grazing-adapted plant community. Based on test runs, we conducted a 310-year spin-up with a randomized climate data sequence from 1980 to 2010 for all scenarios, followed by a 31-year transient simulation from 1980 to 2010. In the RO- and RC-scenario, we prescribed grazing between2000 and 2010 and kept the low-level background grazing from the spin-up for the CO-scenario. Natural fire as part of the local rangeland dynamics was allowed during spin-up and transient simulations.

2.6.2 Rangeland specifics and animal numbers

Based on the herder surveys (see section 2.3), we set livestock to a total of 90 LU for Gabaza and 87.4 for Selwana. The rangeland area was 1431 ha at Gabaza (15.9 ha/LU) and 2128 ha (24.3 ha/LU) at Selwana. At Gabaza, 71% of the rangeland was woodland and 29% grassland, and at Selwana 55% was woodland and 45% grassland (Tab. 1). While rangeland at Selwana

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is one contiguous area, Gabaza's rangeland includes four sub-areas (A1 to A4) with area sizes of 57, 279, 394, and 683 ha. Lacking detailed information, we assumed equal woodland-grassland partitioning for all sub-areas.

2.6.3 Spatiotemporal distribution of livestock

The aDGVM2 required day-based information of the LU number visiting a given hectare. The aDGVM2 models vegetation on individual 1-ha stands with no information exchange between different hectares. Spatiotemporal sequences mimicking animal movement on grazed areas were created to determine animal effects on each individual hectare on any given day as explicit animal movement was not tracked. The generation of hectare-specific grazing sequences is described in the supplementary material. At Gabaza, we established an additional temporal subdivision to determine the duration of animal presence on each sub-area. We assumed active herd relocation between sub-areas (and between rangeland and cropland) and prescribed the use of only one sub-area at a time. Additionally, we partitioned presence time proportionally to sub-area size. Therefore, the average total annual amount of dry matter removed from a given hectare is approximately constant, independent of its location in a small or large sub-area, but resting periods are longer for the smaller sub-areas. Figure 2 illustrates presence/absence on rangeland for both villages and scenarios (RO, RC). The proportional reduction of presence time in the RC-scenario compared to the RO-scenario is illustrated in supplementary Fig. S1.

2.6.4 Simulation of representative hectares

Although we created grazing sequences for all hectares (see supplementary material), computational constraints precluded simulating the total rangeland. We therefore simulated different grazing intensity levels based on total LU visits/ha during the experiment. For each rangeland (sub-)area, we conducted 150 simulations (75 grassland, 75 woodland hectares), with 15 simulations per area and vegetation type ranging around the minimum, maximum, median, 25-percentile and 75-percentile of cumulative LU-numbers/ha over 11 years, respectively. For sub-area A1 at Gabaza, all 57 ha, i.e., the complete sub-area, was simulated. For simulated percentages of (sub-)areas, see Fig. 1a. We conducted 657 simulations for each scenario (CO, RO, RC), i.e., 1971 simulations total.

2.6.5 Feed gap analysis

Consumable grass biomass includes living leaves and stalks, standing dead and reproductive biomass. A minimum amount of each pool is unavailable to grazers as they cannot graze completely down to the ground. For cattle, we defined a limit of 30 g/m^2 of living and dead biomass that needs to remain, respectively, and 10 g/m^2 of seed biomass (see Pfeiffer et al., 2019). Feed gaps occur when demand exceeds available biomass. We calculated average annual demand, consumption, and deficit across all simulated hectares, by vegetation type (i.e., for woodland and grassland hectares), for both villages, and (sub-)areas. In addition, we integrated results results across all simulated hectares to determine overall annual deficits relative to demand to identify interannual differences and demand-specific deficit severity. To investigate deficit frequency, we determined the number of deficit days per year in relation to the total number of days spent on the rangeland within a given year. For the

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RC-scenario, we accounted for reduced livestock grazing time by scaling relative variables, such as the ratio of deficit-days to grazing-days, or the ratio of biomass deficit relative to demand, by the fraction of time animals spent on the rangeland. We also created hectare-scale overviews for biomass consumption and demand to assess variability between hectares, which allowed for comparisons between both villages, as well as sub-areas at Gabaza.

2.7 Performance indicators

For the evaluation of the cropland simulations, we analyzed the temporal grain and straw yield (dry matter) dynamics at both villages and determined site-specific differences in yield patterns and between SQ- and SI-scenarios. Aside from yields, we analyzed SOC status, cropland vegetation cover, and soil-water dynamics. For the rangeland simulations, we considered metrics that describe animal-related aspects and grazing pressure on vegetation, such as grazing frequency and biomass demand relative to consumption. We identified when feed gaps occur and their severity compared to demand. Additionally, we examined the seasonal and interannual dynamics of grass biomass and productivity (NPP, GPP) to determine between-village difference sand between the RO- and RC-scenarios.

3 Results

3.1 Cropland simulation results

3.1.1 Yield comparison between the two villages

Maize grain yield

Village-scale grain yields showed considerable interannual variability (Fig. 3a and b). With a larger arable area, Selwana had higher total yields than Gabaza but lower yields per hectare due to the drier conditions (Fig. 3c and d). The total yield at Gabaza in the SQ-scenario varied between 395.5 t in 2005 and 1252.8 t in 2006 (average: 909.9±250.7 t). Yields per hectare ranged between 1.18 t/ha and 3.73 t/ha (average of 2.71±0.75 t/ha). SI led to a moderate, non-significant average yield increase by factor 1.15±0.07 (Fig. 3e). Straw yield was moderately, but at Selwana not significantly, increased by SI (Fig. 3f). Maize village production at Selwana varied greatly, from 366.9 t in 2001 to 5738.9 t in 2004 (average: 2619.7±1603.0 t). Maize grain yields per hectare at Selwana were 53.2±22.9% lower than at Gabaza, ranging between 0.18 t/ha and 2.85 t/ha (average of 1.30±0.79 t/ha). Compared to Gabaza, SI at Selwana led to a slightly higher average maize yield increase (by factor 1.22±0.30, statistically non-significant), but the response varied considerably between years (Fig. 3e). The highest yield increase at Selwana (factor 1.77) occurred in 2005. However, SI reduced maize yield in 2004 by 11% compared to the SQ-scenario, and to a lesser extent also in 2002 and 2006. At Gabaza, SI consistently increased maize yields.

Cowpea grain yield

The mean cowpea yield in the SQ-scenario at Gabaza was 62.1±23.6 t, with a minimum of 30.4 t in 2004 and a maximum of 96.0 t in 2007, and a mean yield per hectare of 0.96±0.36 t/ha (Fig. 3). In the SI-scenario, grain yield on average increased

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by factor 1.59±0.03 (statistically significant increase at p<0.05; Fig. 3e). The total mean village cowpea grain yield in the SQ-scenario at Selwana was 169.2±91.9 t, with a minimum of 35.6 t in 2005 and a maximum of 328.1 t in 2008. By hectare the average yield was 0.38±0.21 t/ha (minimum: 0.08 t/ha; maximum 0.74 t/ha). SI led to an average non-significant yield increase by a factor of 1.25±0.21.

Peanut grain yield

Gabaza had a village-scale peanut yield of 161.3±27.3 t, with a minimum of 125.2 t in 2005 and a maximum of 213.7 t in 2000 (Fig. 3a). Average yield per hectare was 0.88±0.15 t/ha (minimum: 0.68 t/ha; maximum: 1.17 t/ha; Fig. 3c). SI increased the yield by an average factor of 1.22±0.03 (range: 1.14 to 1.27, increase significant at p<0.05; Fig. 3e). At Selwana, the village-scale peanut yield was 198.6±74.0 t, ranging between 62.6 t in 2003 and 308.7 t in 2000 (Fig. 3b). By hectare, the average yield was 0.45±0.17 t/ha (minimum: 0.14 t/ha; maximum 0.70 t/ha; (Fig. 3d). On average, SI increased peanut yields at Selwana by a factor of 1.28±0.32 (statistically non-significant), with the strongest positive effect in 2001 (factor 1.66 increase; Fig. 3e). However, in 2005 yield at Selwana was less than half that of of the SQ-scenario.

Effect of SI measures on grain yields - summary comparison

For cowpea and peanut, SI had a stronger positive effect at Gabaza for relative and hectare-specific increases. Cowpea benefited the most with a factorial increase of 1.59±0.03 (absolute yield increase per hectare of 0.57±0.23 t/ha). With the highest hectare-specific yields of all crops, the moderate increase by a factor of 1.15±0.07 led to an overall increase of 0.38t/ha for maize, while the relative increase by a factor of 1.22±0.03 for peanut corresponded to a yield increase of 0.18±0.06 t/ha. At Selwana, hectare-specific yield increase was highest for maize (0.20±0.37 t/ha; relative increase by factor 1.22±0.30), followed by peanut (1.15±0.11 t/ha; relative increase by a factor of 1.28±0.32) and cowpea (0.10±0.10 t/ha; relative increase by a factor of 1.25±0.21). The crop-type specific responses also caused a slight shift in the relative contribution of each crop type to the total village-level yield (see Fig. S2).

SI led to a statistically significant increase in village-scale yield at Gabaza for cowpea and peanut, but not for maize (Welch two-sample t-test, p<0.05). No crop type at Selwana showed a significant increase. Moreover, interannual variability of SI-related yield effects was more pronounced and even negative in some years.

3.1.2 Soil organic carbon (SOC), cropland vegetation cover, and soil water

Cropland SOC gradually decreased irrespective of management (Fig. 4). At Gabaza, SOC declined by 4.68% from 7.52 kg C/m^2 to 7.17 kg C/m^2 in the SQ-scenario. SI reduced SOC-loss to 3.70%, with 7.24 kg C/m^2 left in 2010. On average,cropland soil at Selwana stored 1.39 ± 0.06 kg C/m^2 less than at Gabaza, and C-loss was 6.18% in the SQ-scenario (from 6.10 kg C/m^2 in 1998 to 5.72 kg C/m^2 in 2010).SI only had a minor effect on SOC-loss at Selwana (5.59% loss, 5.76 kg C/m^2 in 2010). At the village scale, cropland soils under SI had 427 (Gabaza) and 1030 (Selwana) tons more carbon stored in 2010 than under SQ.

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Average green leaf area index (LAI) on cropland varied seasonally and interannually (Fig. 5). Monthly values at Gabaza (Fig. 5a) were generally higher than at Selwana (Fig. 5b). SI had a moderately positive but statistically non-significant effect on LAI, and the highest canopy-cover values occurred during the growing period from December to March. After crop harvest,weed infestation drove cropland LAI during the dry season.

Extractable soil water (ESW) was generally higher at Gabaza (Fig.5c,d). Minimum values occurred in August and September and increased throughout the wet season before gradually declining again. At both locations, SI tended to reduce ESW due to the higher vegetation cover and biomass simulated in the scenario. However, the difference between the SQ- and SI-scenario was non-significant.

3.2 Rangeland simulation results

3.2.1 Biomass demand, consumption, grazing frequency

Hectare-specific average annual biomass demand was lower at Selwana (Tab. 2a). There, the average annual demand and standard deviation across simulated grassland hectares ranged between 0.29±0.12 and 0.34±0.13 t/ha in the rangeland-only (RO) scenario and between 0.07±0.07 and 0.19±0.09 t/ha in the rangeland-cropland (RC) scenario (0.10±0.04 to 0.11±0.05 t/ha vs. 0.03±0.02 to 0.07±0.04 t/ha on woodland hectares, respectively).

At Gabaza, the average annual demand ranged between 0.47±0.16 t/ha to 0.63±0.16 t/ha on grassland in the RO-scenario and between 0.13±0.09 t/ha to 0.34±0.13 t/ha in the RC-scenario (0.17±0.09 to 0.24±0.07 t/ha for woodland hectares in the RO-scenario, and from 0.05±0.04 to 0.14±0.07 t/ha in the RC-scenario). Figs. S3 and S4 illustrate the average annual hectare-specific demand for the scenarios.

On average, grazers visited each hectare at Selwana on 8-9 d/yr in the RO-scenario (Tab. 2b), and on to 2-6 d/yr in the RC-scenario with cropland access. At Gabaza, LU on average frequented each hectare on 11-14 d/yr in the RO-scenario and on3-8 d/yr in the RC-scenario, except for the smallest sub-area A1 where the average visit frequency was between 7-11 d/yr in the RO-scenario (annual presence on A1: 15 d/yr), and between 3-6 d/yr in the RC-scenario (presence on A1: 3-8 d/yr, depending on the year).

Despite a similar frequency of visit, the average consumption on woodland was lower than on grassland (Tab. 2c) due to the lower number of visiting animals. Average daily biomass consumption on affected hectares was comparable between the RO-scenario and RC-scenario as on a per-day-basis the same number of animals per area was present during both scenarios. Differences in annual biomass consumption between scenarios only emerged due to the shortened presence times per area in the RC-scenario (Tab. 2d).

3.2.2 Feed gaps on rangeland

Across all simulated hectares, the annual demand-specific deficit (gap between supply and demand) at Selwana ranged between 0.2 and 11.4% in the RO-scenario (Fig. 6a). In the RC-scenario, the deficit declined to values between 0-5.1%, partially due to the shorter herd presence on the rangeland. Gabaza, where the average cattle density per ha was 1.53 times higher, had higher

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Table 2. Average annual per-hectare values and standard deviation across hectares for the years with lowest (left value) and highest (right value) mean value. a) average annual biomass demand per hectare; b) average number of days a hectare was frequented by grazers; c) biomass removed by grazers on a grazing day; d) annual grazed biomass per hectare. GL: grassland; WL: woodland; RO: rangeland-only scenario; RC: rangeland+cropland scenario.

Site/Area	GL hectares RO	GL hectares RC	WL hectares RO	WL hectares RC
		a) Annual biomass demand [$t\ ha^{-1}\ yr^{-1}$]		
Selwana	0.29±0.12 to 0.34±0.13	0.07±0.09 to 0.19±0.11	0.10±0.04 to 0.11±0.05	0.03±0.03 to 0.07±0.03
Gabaza A1	0.47±0.16 to 0.63±0.16	0.18±0.10 to 0.33±0.11	0.18±0.08 to 0.24±0.09	0.08±0.04 to 0.13±0.06
Gabaza A2	0.52±0.17 to 0.57±0.17	0.22±0.11 to 0.34±0.09	0.19±0.07 to 0.22±0.06	0.08±0.05 to 0.14±0.04
Gabaza A3	0.52±0.16 to 0.60±0.18	0.20±0.14 to 0.34±0.14	0.18±0.7 to 0.22±0.07	0.06±0.05 to 0.12±0.04
Gabaza A4	0.50±0.15 to 0.59±0.23	0.13±0.13 to 0.31±0.10	0.17±0.07 to 0.21±0.08	0.05±0.05 to 0.11±0.04
		b) Grazing days [$ha^{-1}\ yr^{-1}$]		
Selwana	8.3±2.6 to 9.2±3.1	2.1±2.1 tp 5.5±1.5	8.2±3.3 to 9.3±3.1	2.3±1.9 to 5.6±1.5
Gabaza A1	7.4±1.9 to 10.6±1.0	2.9±1.2 to 5.8±1.3	7.5±2.0 to 10.5±1.5	3.0±1.3 to 5.6±1.3
Gabaza A2	11.8±3.2 to 13.9±3.2	5.0±2.0 to 8.0±2.1	11.3±2.9 to 13.7±3.1	5.5±2.3 to 8.1±2.4
Gabaza A3	11.9±3.1 to 13.9±3.2	5.2±2.3 to 8.1±2.3	11.8±3.5 to 13.9±3.1	4.9±2.5 to 7.5±2.2
Gabaza A4	11.1±3.9 to 13.2±3.3	2.6±2.3 to 7.4±1.7	12.0±3.5 to 13.5±3.8	3.1±2.2 to 7.4±2.0
		c) Daily removed biomass [$kg\ ha^{-1}\ day^{-1}$]		
Selwana	29.5±24.3 to 36.7±28.8	29.8±27.3 to 34.2±25.7	11.2±9.1 to 12.4±9.8	10.9±10.7 to 13.0±8.4
Gabaza A1	38.7±28.7 to 73.8±49.1	44.7±28.3 to 64.4 ±39.4	18.7±12.9 to 28.5±19.9	20.5±16.2 to 32.6±15.0
Gabaza A2	31.2±29.1 to 45.6±36.0	37.6±27.0 to 43.7±37.2	13.5±11.9 to 17.4±13.2	13.3±11.9 to 16.9±10.3
Gabaza A3	38.0±30.5 to 44.5±27.9	30.4±25.5 to 45.4±26.4	13.9±11.7 to 17.0±14.2	12.4±9.9 to 18.1±8.8
Gabaza A4	31.0±28.1 to 42.5±38.2	29.6±30.8 to 46.2±26.5	12.4±10.9 to 16.3±13.1	12.5±13.2 to 16.5±10.6
		d) Annual removed biomass [$t\ ha^{-1}\ yr^{-1}$]		
Selwana	0.26±0.11 to 0.34±0.13	0.07±0.08 to 0.18±0.06	0.10±0.04 to 0.11±0.05	0.03±0.3 to 0.07±0.02
Gabaza A1	0.37±0.19 to 0.63±0.16	0.18±0.10 to 0.33±0.11	0.18±0.08 to 0.24±0.09	0.08±0.04 to 0.13±0.06
Gabaza A2	0.39±0.17 to 0.57±0.17	0.22±0.12 to 0.33±0.09	0.17±0.06 to 0.22±0.06	0.08±0.05 to 0.14±0.04
Gabaza A3	0.46±0.19 to 0.60±0.18	0.19±0.11 to 0.32±0.12	0.18±0.06 to 0.22±0.07	0.06±0.05 to 0.12±0.03
Gabaza A4	0.38±0.17 to 0.53±0.22	0.11±0.17 to 0.30±1.0	0.15±0.06 to 0.20±0.07	0.05±0.04 to 0.10±0.05

relative deficits. Moreover, Gabaza has a higher relative woodland proportion (Tab. 1). Demand-specific deficits at Gabaza were between 0.4 and 17.5% in the RO-scenario (Fig. 6b) and declined to values between 0-8.0% in the RC-scenario. Years with higher deficits, such as 2002, 2003, 2005, and 2008, coincide with low annual precipitation at both sites (Fig. 1b). The maximum deficits occurred in 2003, the second dry year in a row after 2002. For relative deficits separate for grassland and woodland hectares, see Fig. S5.

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Integrated across all simulated hectares, the timeline of the percentage of grazing days with a deficit resembles the one for relative deficits (compare Fig. 6c and a, and d and b). Between 0.6 and 11.5% of grazing days had a deficit in the RO-scenario at Selwana. The RC-scenario reduced this to a range from 0.0 to 5.2% of total days. At Gabaza, the higher grazing pressure caused more deficit days. Here, the RO-scenario resulted in a range from 0.5 to 17.0% of grazing days, with a reduction to 0.0-6.6% in the RC-scenario. For a presentation by vegetation type, see Fig. S6. Deficit timing showed a clear seasonal pattern (Fig. 6e,f). Monthly deficits in the RO-scenario were lowest between March and June and highest in October/November before declining towards December. While both villages had a similar seasonal pattern, the demand-specific monthly deficits were higher at Gabaza, particularly from September to November. Cropland pasturing between ca. April to October (see Fig. 1e,f) avoided deficits during these months. However, it also reduced the deficit size during rangeland presence (compare scenario RO vs. RC in Fig. 6e,f). Deficits showed a delay of 2-3 months relative to precipitation (Fig. 1c,d), i.e., the maximum occurred delayed after the end of the dry season, when precipitation increased again. Similarly, the lowest deficits in March /April occurred ca. 2 months after peak precipitation.

3.2.3 Temporal dynamics of grass biomass

Consumable grass biomass provision was distinctively seasonal (Figs. 7, 8). Peak biomass occurred between February to March, and minimum availability developed towards the end of the dry season in October/November. Overall biomass availability was lower at Selwana than at Gabaza, and woodland hectares produced less consumable biomass than grassland hectares. Consumable biomass also greatly varied between years. As the second of two consecutive dry years, 2003 had the lowest biomass from the 11 years. Grazing had a minor effect on across-hectare average consumable biomass (compare scenario averages and standard deviations in Figs. 7, 8). Differences in fire occurrence between scenarios also caused biomass differences (see Figs. S7 and S8).

3.2.4 Rangeland productivity (NPP, GPP)

For Selwana grassland, the average annual GPP in the control ranged between 3.13±1.45 to 11.18±4.09 t/ha, whereas Gabaza had values between 3.56±1.88 to 15.79±6.53 t/ha (Tab. S2, Fig. S9). On woodland, hectare-specific grass-layer GPP was lower and ranged between 1.15±0.6 to 3.64±1.71 t/ha at Selwana, and between 1.30±0.65 to 4.70±1.63 t/ha at Gabaza (Tab. S2, Fig. S10). Differences between scenarios were statistically non-significant (two-sided t-test, $p<0.05$).

Annual grassland NPP at Selwana varied considerably and ranged between 1.24±0.46 to 6.02±2.25 t/ha in the control scenario. Annual grassland NPP at Gabaza was higher, with values between 1.44±0.64 to 8.71±3.79 t/ha (Tab. S3, Fig. S11). We also simulated this pattern for woodland hectares, where average annual NPP ranged between 0.40±0.26 to 1.94±0.93 t/ha at Selwana, and between 0.48±0.25 to 2.59±0.91 t/ha at Gabaza (Tab. S3, Fig. S12). The RO- and RC-scenario did not differ significantly (two-sided t-test, $p<0.05$) from the control, except for the years 2005 and 2007 in the RC-scenario for Selwana grassland hectares, and the year 2008 in the RO-scenario for the woodland hectares of sub-area A1 at Gabaza.

GPP normalized for living leaf biomass (LLBM) had annual values approximately between 7 and 13 g C/g LLBM (see Tab. S4 and Figs. S13, S14), and between 2 and 8 g C/g LLBM for normalized NPP (see Tab. S5 and Figs. S15, S16). Values of biomass-specific GPP and NPP were comparable between grassland and woodland, i.e., grass on woodland was as productive as grass on grassland. Different from the hectare-specific GPP and NPP values, grazing frequently caused significantly (two-sided t-test with $p<0.05$) higher average biomass-normalized GPP and NPP values relative to control (see Figs. S13, S14, S15, and S16). This effect was usually stronger in the RO-scenario. Plot-level GPP and NPP showed pronounced seasonality, and monthly values varied strongly between years (Figs. S17, S18, S19, and S20).

We saw similar seasonality for biomass-specific monthly GPP and NPP (Figs: S21, S22, S23, S24) with minimum values in June and a gradual increase to the December maximum. Values gradually declined from January to March and rapidly towards June. Integrated across all simulated hectares, annual biomass consumption relative to NPP varied between years and was lower at Selwana (Fig. 9). The highest ratios occurred in the dry years 2002, 2005, and 2008 (Fig. S11, S12), with ratios of 0.19, 0.17, and 0.22 in the RO-scenario at Selwana (0.09, 0.08, and 0.10 in the RC-scenario), and ratios of 0.23, 0.21, and 0.30 in the RO-scenario at Gabaza (0.10, 0.12 and 0.14 in the RC-scenario), respectively. The annual consumption/NPP ratio was approximately halved in the RC-scenario compared to the RO-scenario (reduction by a factor of 2.14 ± 0.59 at Selwana; 2.07 ± 0.18 at Gabaza).

4 Discussion

The UN Sustainable Development Goals (SDGs; UN General Assembly, 2015) include alleviating poverty (SDG1), reducing hunger and enhancing food production (SDG2), and reducing habitat loss and degradation to preserve terrestrial ecosystems and biodiversity (SDG13). These are among the most desirable goals for rural areas in southern Africa. Agricultural scientists emphasize SI as a way to improve cropland productivity (e.g., Mueller et al., 2012; Cassman and Grassini, 2020) while reducing environmental impacts and maintaining ESS and ESF (Tilman et al., 2011; Tscharntke et al., 2012). Given that smallholder farming provides more than 80% of the food supply in sub-Saharan Africa and Asia (Walpole et al., 2013), SI measure adaptation in smallholder farming systems needs a special focus and an integrated system approach with a range of possible management interventions (Vanlauwe and Dobermann, 2020). With more than 500 million smallholder farms worldwide sustaining the livelihoods of more than two billion people (Walpole et al., 2013), smallholder farming needs explicit consideration when discussing SI measures. Landscape-based integrative adaptations linking agricultural and natural systems are required to ensure the continued provision of ESS and help smallholders adapt to climate change (Harvey et al., 2013; Vignola et al., 2015). In our study, we present an example that illustrates how linked crop and rangeland modeling can address research questions on the sustainable management of smallholder farming systems at the landscape level. We focused on research questions revolving around (i) the effect of minimum levels of intensification on crop production, (ii) the trade-offs and opportunities of combined versus separated management of cropland and rangeland for cattle production.

4.1 Impact of minimum SI measures on cropland ESS

The minimum intensification measures implemented in our simulations had minor to moderate effects on cropland ESS. Carbon sequestration increased moderately due to higher yields and SOC input. However, SI-measures could result in yield losses in

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dry years due to enhanced crop growth and associated increased water demand compared to SQ. While SI-measures increased SOC sequestration compared to the SQ-scenario at the end of the 11-year simulation period, SI could not reverse the decreasing trend and cropland soils remained a carbon source, indicating yet too low input of organic material to the soil. Although SI had a negative effect on the amount of plant-available soil water, the interannual variability was larger than the difference caused by SI.

With an average significant increase of 59%, cowpea yields at Gabaza reacted most strongly to SI. Weeding, fertilizer and manure input moderately improved productivity when soil water was not limiting, with potential for higher increases with yet more nitrogen and additional phosphorus input (the latter often a major limitation factor in the province's smallholder fields). However, at Selwana, SI measures sometimes reduced yields compared to SQ. Improved nutrient provision boosts early-stage crop development and results in increased biomass accumulation compared to SQ without fertilizer input. During later stages, the augmented biomass requires more soil water, which can reduce yields and even cause crop failure in years where water becomes limited during later crop development stages. Without irrigation, crops cannot benefit from the additional nutrients from soil amendments under water limitation. Targeted irrigation could make SI measures more effective but is often unavailable to smallholders. From our survey work, two out of 140 smallholders irrigated. However, some initiatives show promise in making irrigation feasible for smallholder farmers, for example through public investments in South Africa, public-private partnerships in Zimbabwe, and SI business models in Tanzania (Hanjra and Williams, 2020).

Plant water availability also depends on soil water holding capacity (SWC), which is determined by soil texture, SOC, soil flora and fauna, and soil structure. Particularly on sandy soils, organic matter substantially improves SWC. In addition, loosening compacted soils is an effective way to increase infiltration, create a favorable structure, and increase SWC. While farmers have little influence on soil texture, they can nonetheless improve soil structure with considerable SWC-enhancing effects (Suzuki et al., 2007). Key to amending soil water infiltration and storage is to increase soil organic matter (SOM) by adding plant or animal material, which in turn also reduces soil erosion (Mohler and Johnson, 2009). In addition, utilizing certain aspects of conservation agriculture (CA) practices, such as diversified crop rotations and crop residue retention can also enhance SOM development, crop yields, and climate resilience (Franzluebbers, 2002; Lehman et al., 2017; Williams et al., 2018; Hoffmann et al., 2020). Participatory research with farmers could help identify realistic pathways for SOM-enhancing interventions to be included in future simulations that explore SI for smallholder systems.

4.2 Feed gaps at village-level and village-specific differences

Feed gaps occurred in both villages. At Gabaza, higher MAP yielded higher productivity and biomass availability for grazers than the arid rangeland at Selwana. However, higher cattle density at Gabaza compared to Selwana implied higher grazing pressure, which counteracted more favorable environmental conditions and caused higher average deficits at Gabaza.

On average, a given rangeland hectare was grazed on very few days a year (Tab. 2b). This implies that there was ample time for biomass recovery. Additionally, average hectare-specific consumption was low compared to productivity and had no severe impact on biomass, GPP, and NPP (Figs. 7, 8, S9, S10, S11, S12). These indicators do not hint at a general overgrazing problem, where we would expect a drastic reduction of biomass and rangeland productivity. However, due to the lack of explicit spatial movement patterns and information on preferred cattle resting and grazing places, we likely underestimated imbalances in rangeland usage, i.e., we may not have captured overgrazing on specific areas, e.g., next to resting or watering places. Here a long-term monitoring of cattle movement using GPS collars (Bailey et al., 2018) could reveal such patterns and allow for their incorporation in rangeland simulations.

Substantial feed gaps despite little biomass and productivity reductions seem contradictory. Feed shortage timing explains how deficits occur despite moderate stocking densities. Agreeing with herder statements, we simulated the largest shortfalls at the dry-to-wet season transition (Fig. 6e,f). This also agrees with the findings of Lamega et al. (2021) that mixed crop-livestock farmers in the drier parts of Limpopo perceive spring as the time with the most pronounced feed gaps. In most years, biomass shortage started in August and intensified until October/November before gradually declining. The mid to late wet season and early dry season usually experienced minimal deficits. Therefore, feed shortages occurred with 2-3 month delays relative to precipitation seasonality, i.e., they were most prominent when precipitation started increasing, and lowest in March/April approximately two months after peak precipitation. The delay is the result of the time-lagged response of vegetation to water availability. Throughout the dry season, living biomass gradually declines and livestock increasingly consumes dead grass. Towards the end of the dry season, both dead and living grass biomass reserves become exhausted. After the onset of rains, new biomass develops gradually and is still insufficient to cover animal demand.

4.3 Closing feed gaps with integrated management of cropland and rangeland

Our results show that dry-season residue grazing on cropland can reduce feed shortages. Dry-season access to cropland often more than halved the annual feed gap and shortened the feed scarcity period. Moreover, dead grass on the rangeland lasted longer into the early wet season, which reduced the feed gap between September and November. Eliminating feed gaps would require cattle to return to the rangeland at a later stage than simulated, i.e., when early re-growth of grasses has terminated. However, a later return would collide with crop planting dates. For sufficient feed supply during the transition period, we therefore recommend storing part of the crop residues directly after harvest, given availability of storage space and appropriate storage possibilities. These residues can then feed cattle until rangeland provides sufficient biomass. Controlled feeding also allows for the treatment of stover to improve nutrient and crude protein supply, to increase feed intake and reduce dry-season weight loss in cattle (Smith, 2002). Digestibility, energy value, nutrients, and protein content also vary with crop residue type. Therefore, residue mixing can additionally improve livestock supply. Ideally, livestock farmers should provide licks and ensure gradual adaptation to residues to avoid typical problems associated with crop residue feeding (Hofmeyr, 2020). In this context, well-trained extension staff who provides such information for farmers is crucial.

4.4 Identification of management strategies for sustained provision of ESF and ESS at the landscape-level

Linking cropland and rangeland modeling helped analyze individual management scenarios for both land use types and allowed for the identification of management strategies that maximize benefits at the landscape level. In this study, a comparison of village level crop residue quantities with the feed gap from rangeland grazing revealed how much of the dry season feed gap can be closed with residue grazing. However, consideration of time-dependent aspects also showed that quantities are only a

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partial aspect that may lead to incomplete conclusions. The timing of the most severe feed deficit at the beginning of the wet season coincides with the start of the crop planting season. Therefore, a complete elimination of feed deficits requires off-field access to previously collected crop residue.

Dry-season crop residue grazing can reduce feed gaps and accelerate nutrient turnover via manure dropping. The simulated village-level crop residues provided feed supply and additionally allowed SOM formation. However, neither the SQ- nor the SI-scenario had enough carbon input to reverse the decreasing SOC trend, but SI-measures reduced SOC loss rates. Although we did not conduct crop growth simulations without cattle residue grazing, the comparably low yields and nutrient input levels suggest that avoiding SOC-loss may be challenging even without cattle presence. Implementation of context-specific conservation agriculture measures may improve SOC formation and soil water availability.

Moderate rangeland grazing stimulated biomass-specific grass NPP by triggering biomass re-growth and growth overcompensation. Grazing removes dead biomass, reduces the LAI of living grasses and self-shading within the grass layer, and increases leaf area-specific productivity. Re-growth can also indirectly increase leaf-specific productivity because young leaf tissue tends to be high in nitrogen and photosynthetically more active than old leaves (Kitajima et al., 1997; Mediavilla and A., 2003). However, aDGVM2 does not currently capture this last effect.

Based on our results, we propose the following strategies to ensure the sustained provision of landscape-level ESF and ESS: (1) Apply the minimal SI measures prescribed in our simulations and considered feasible for smallholders at our study villages to moderately increase yields of the staple crops. To avoid the negative effects of SI measures due to water limitation, the adoption of deficit irrigation would be ideal, combined with water conservation measures, runoff prevention, rainwater harvesting, and soil amendments to increase soil water storage capacity, in particular where irrigation is not possible. (2) To reduce dry-season grazing deficits, we propose to give cattle access to cropland and allow crop residue grazing. At the beginning of the crop planting season, post-harvest collected crop residues can be offered off-field to avoid animal deficits and allow for a quick build-up of new grass biomass by alleviating grazing pressure on the rangeland.

5 Conclusions

Holistic crop-livestock management of highly diverse smallholder farming systems in semi-arid ecosystems is crucial to ensure the continued provision of ESF and ESS. Here, the presented linked cropland-rangeland simulations can identify potential pathways towards the SI of crop production and reduction of livestock feed gaps. We found that modest SI measures – deemed feasible for the smallholder farmers in question - can increase yields and SOC sequestration; yet, water limitation during later-stage crop development can counteract SI measures without adequate irrigation or measures to conserve water and increase soil water holding capacity. We found that dry-season cropland residue grazing can substantially reduce feed deficits. However, the most severe rangeland feed gaps occurred at the beginning of the wet season when grass biomass re-growth was at an early stage. Both findings have marked implications at the policy level and call for appropriate actions. If crop residues are abundant, partial post-harvest collection, storage, and provision of residues as feed during the dry-to-wet season transition period could reduce grazing pressure during early rangeland vegetation development. Research approaches that capture

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landscape-level interactions and synergies are crucial as climate change impacts and extreme events become more severe. The future climate resilience of ESF and ESS needs a landscape-scale evaluation to identify effective mitigation and adaptation strategies. Targeted experimental work and environmental monitoring allows for the evaluation of model components for new scenarios. Subsequently, an updated integrative modeling framework as suggested by Rötter et al. (2021) can be applied to test different climate change and management scenarios. Further development should include an animal physiology model to simulate the dynamics of animal growth, reproduction and health condition based on nutrition status. Furthermore, incorporating agent-based modeling could improve the representation of animal behavior on the rangeland and account for interactive decision-processes made by human agents based on both economic and ecological criteria. Likewise, further management options could be included, such as the identification and sowing of suitable ”dry season cover crops“ that are beneficial for animal nutrition and soil improvement.

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Competing interests. The authors declare that they have no conflict of interest.

Author contributions. MP, MH, RR and SS conceived the study. MP and MH conducted the aDGVM2 and APSIM simulations. MP, MH and WN conducted the analysis of the simulation results. MP led the writing of this article. MH, WN, JI, KA, JO and RR were involved in and contributed to the field survey campaigns and data collection. All authors contributed to the writing of this article.

Code availability. The presented data and data analysis scripts will be made available in the SASSCAL data and information portal upon publication. The aDGVM2 code is available upon request from the authors.

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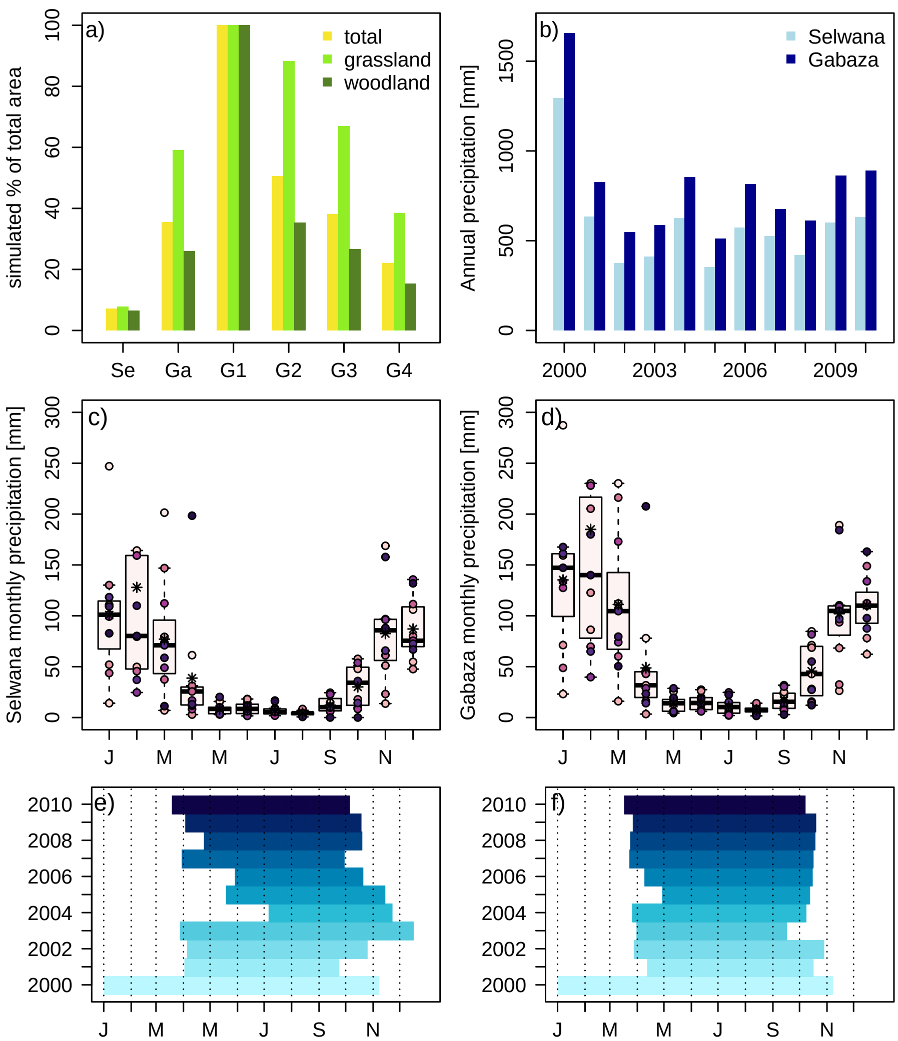

Figure 1. Simulated area percentages for the different sites and (sub-)areas (panel a), and annual precipitation for the years 2000-2010 for Selwana and Gabaza from the AgMERRA climatology used to drive APSIM and aDGVM2 simulations (panel b). Panels c) and d) show monthly precipitation at Selwana and Gabaza, respectively, where stars indicate the 2000-2010 average, the dots the individual annual values. Panels e) and f) show the annual timelines of animal presence on cropland in the RC-scenario. A maximum of 150 hectares (75 grassland and 75 woodland hectares) was simulated per (sub-)area, amounting to the shown simulated percentages of total area. Abbreviations: SE: Selwana; Ga: Gabaza; Numbers for Ga indicate sub-areas. For sub-area Ga1 (total size 57 ha) we simulated all individual hectares of the sub-area.

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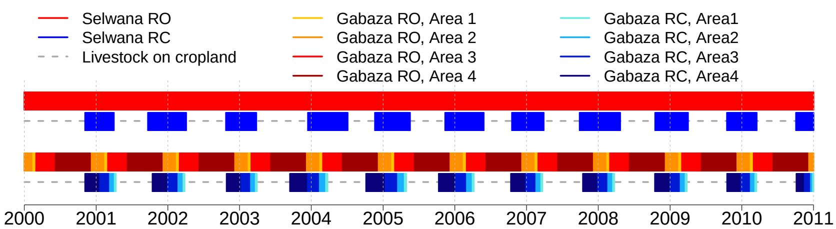

Figure 2. Livestock presence times on communal rangeland. Red-hued bars illustrate times of rangeland presence in the RO-scenario, blue-hued bars show rangeland presence/crop growth period in the RC/SQ-scenario, dashed grey lines indicate animal presence on cropland. For Gabaza (bottom pair of bar sequences), the different color hues show how animal presence on the four sub-areas. Animal presence time on sub-areas is proportional to sub-area size.

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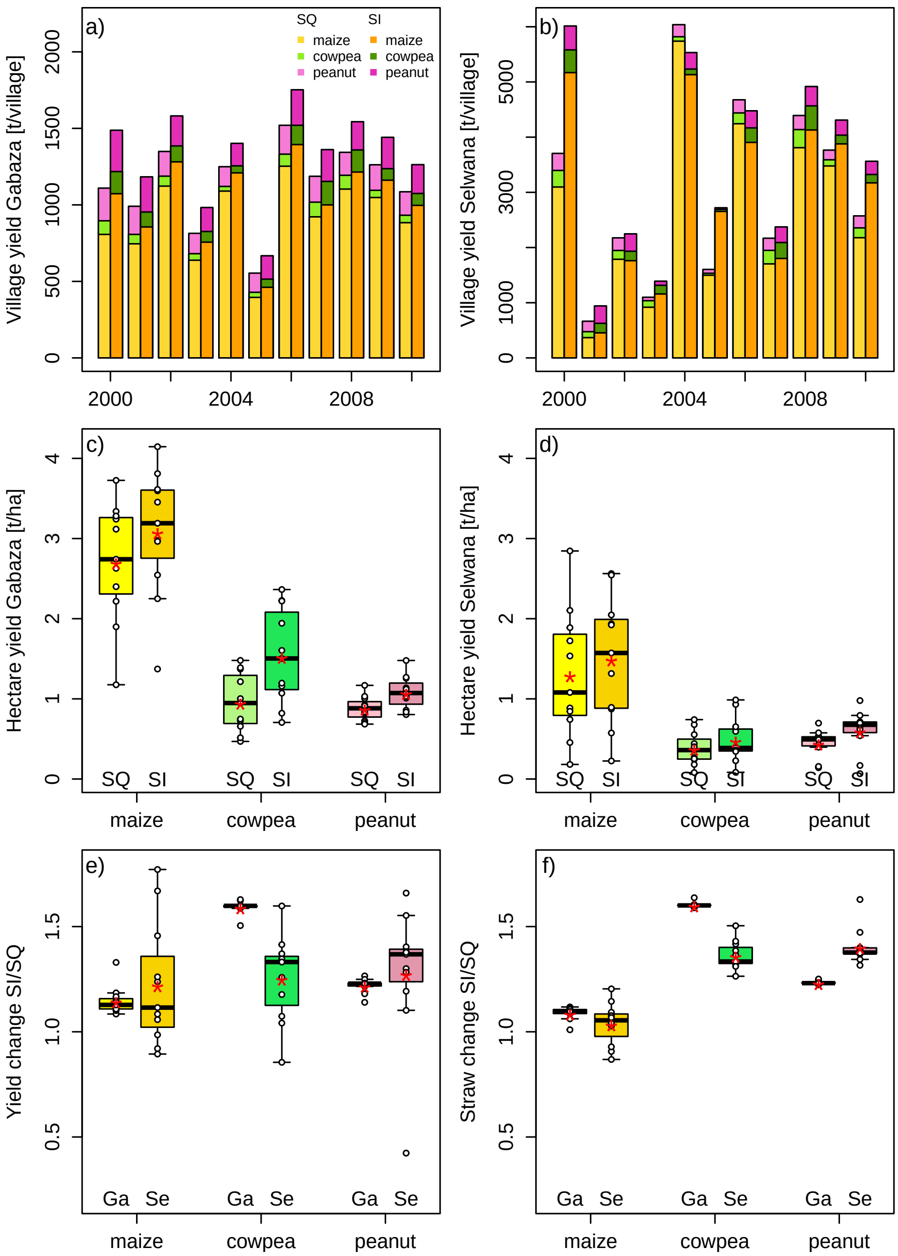

Figure 3. Time series of village-scale crop grain yields for Gabaza (panel a) and Selwana (panel b) under Status Quo management (SQ) and sustainable intensification (SI), and hectare-specific grain yields at Gabaza (panel c) and Selwana (panel d). Panels e) and f) summarize the change in grain yield and straw quantity between SI- and SQ-scenario at Gabaza (Ga) and Selwana (Se) for maize, cowpea and peanut, respectively. White dots in panels c) to f) depict the values of individual years, red asterisks the mean value.

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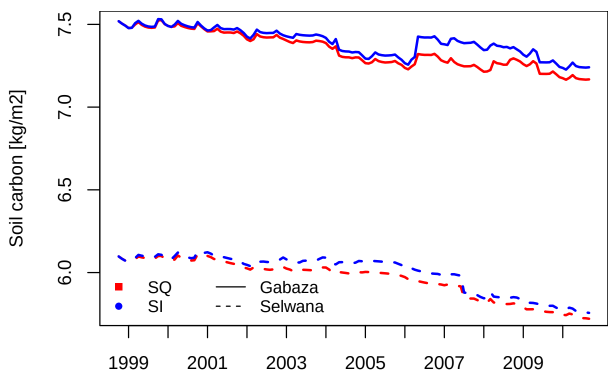

Figure 4. Time series of cropland soil organic matter (SOC) content at Gabaza and Selwana.

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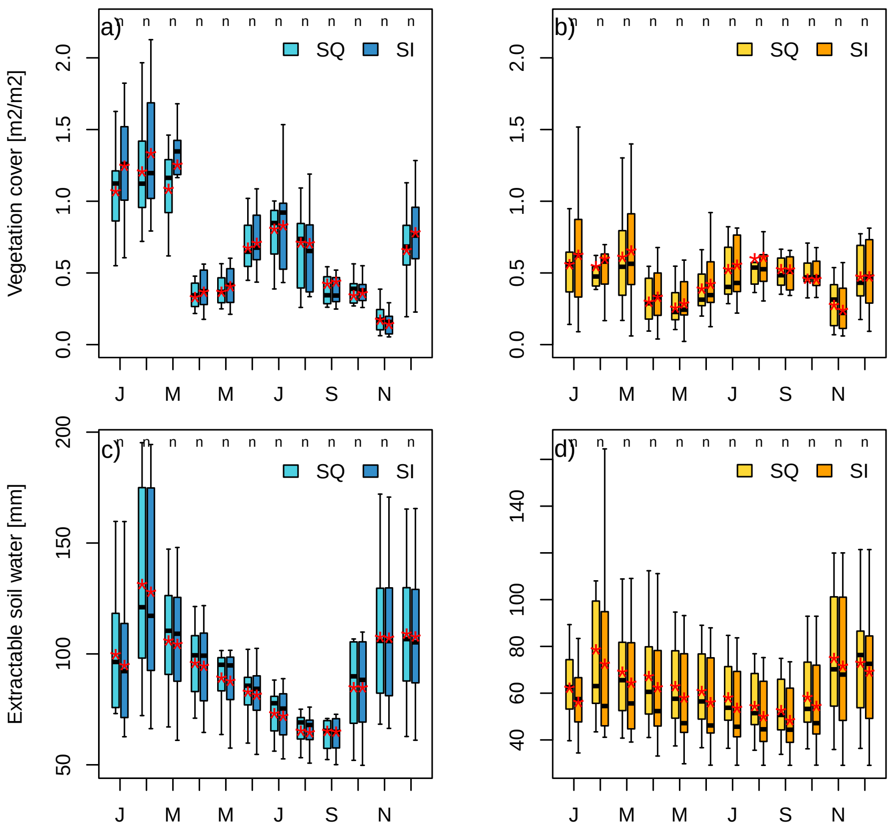

Figure 5. MMonthly cropland leaf area index (LAI) at Gabaza (panel a) and Selwana (panel b), and monthly extractable soil water for Gabaza (panel c) and Selwana (panel d). SQ: Status quo management; SI: minimum sustainable intensification; n: difference non-significant between SQ and SI. Red asterisks: mean values.

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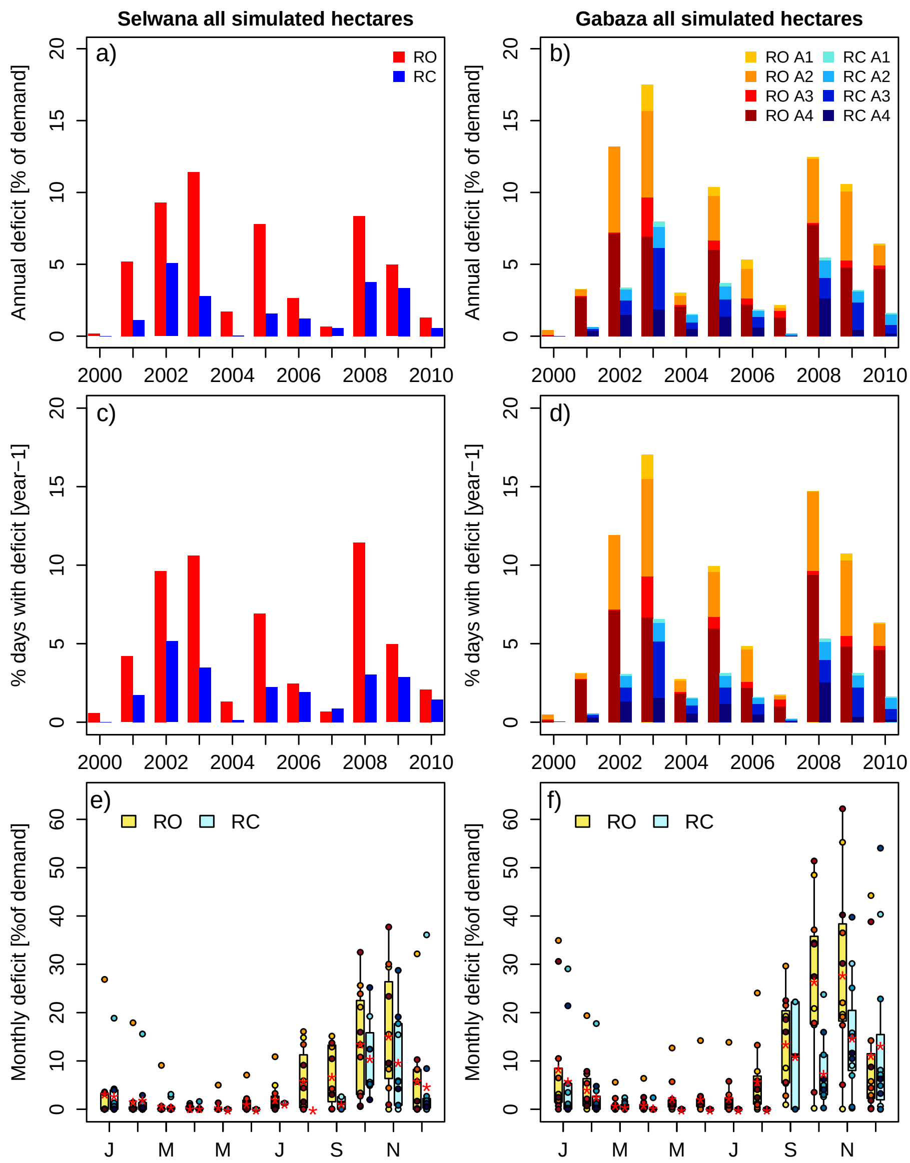

Figure 6. Demand-specific annual deficit across all simulated hectares, and percentage of grazing days integrated across all simulated hectares that had a deficit (irrespective of the size of the deficit), relative to the total grazing days within a year. Panel a) shows relative deficits for Selwana, panel b) shows relative deficits for Gabaza; Panel c) shows percentage of grazing days with deficit for Selwana, panel d) shows percentage of grazing days for Gabaza. Subdivisions of bars in panel b) and d) indicate the relative contribution of each sub-area to the site-scale annual deficit and days with deficit, respectively. Panels e) and f) show the monthly demand-specific deficits across all simulated hectares per village for Gabaza and Selwana, respectively. Red asterisks: mean values; White dots: annual values.

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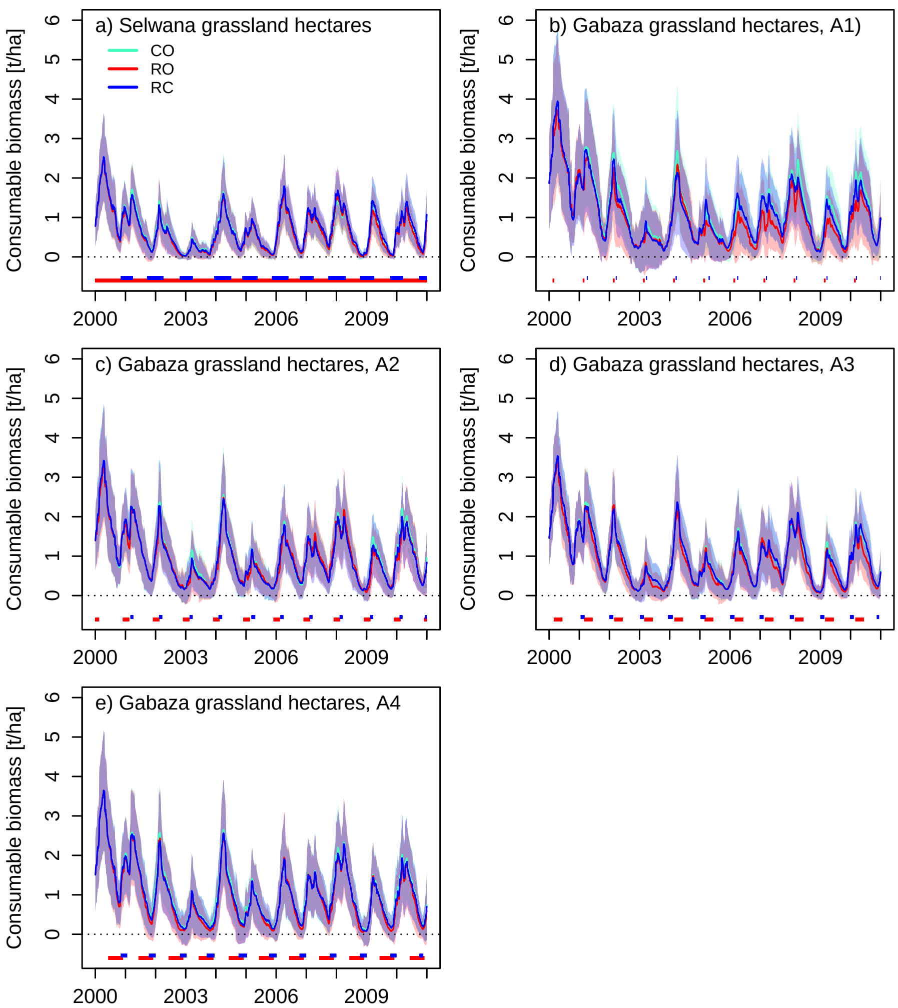

Figure 7. Temporal dynamics of average consumable grass biomass on simulated grassland hectares (living+dead standing grass leaf biomass+reproductive biomass, reduced by the minimum amount that is not available to grazers, i.e., 0.3 t/h for living and dead grass biomass, respectively, and 0.1 t/ha of reproductive biomass). Lines denote the mean across all simulated hectares, shaded areas show the standard deviation. The colored horizontal lines denote the animal presence times for the RO- and RC-scenario.

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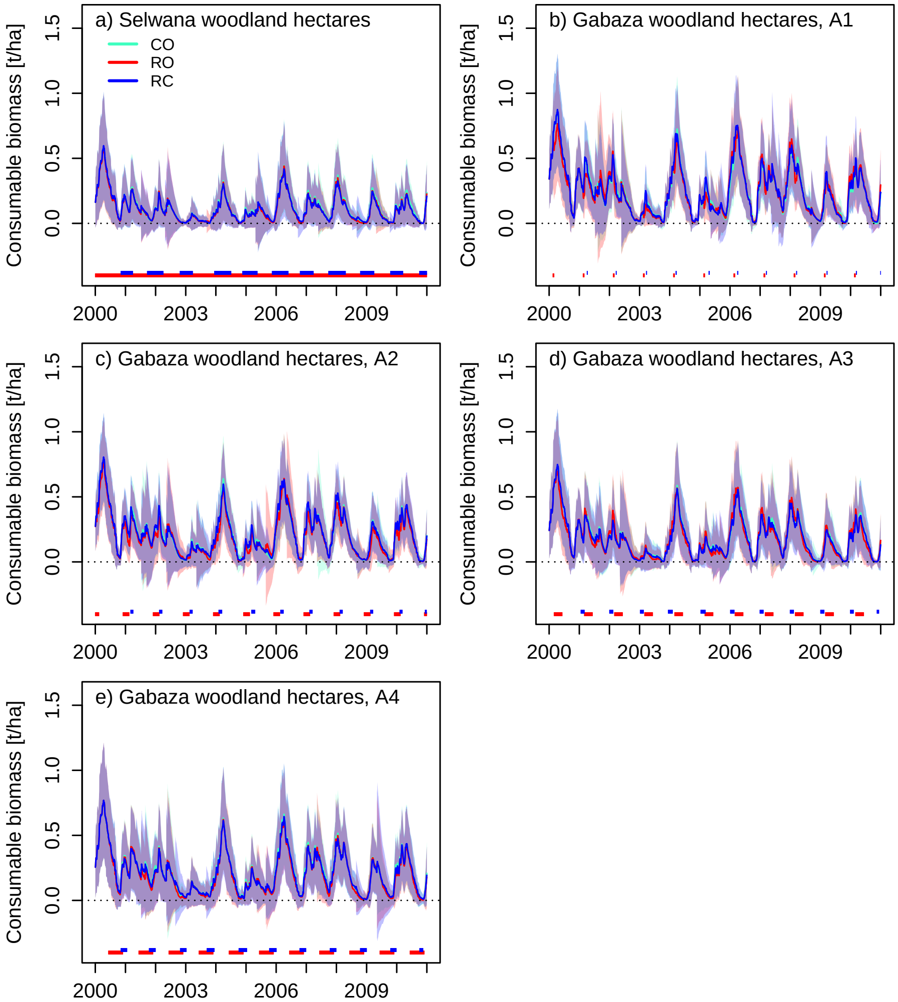

Figure 8. Temporal dynamics of average consumable grass biomass on simulated woodland hectares (living+dead standing grass leaf biomass+reproductive biomass, reduced by the minimum amount that is not available to grazers, i.e., 0.3 t/h for living and dead grass biomass, respectively, and 0.1 t/ha of reproductive biomass). Lines denote the mean across all simulated hectares, shaded areas the standard deviation. The horizontal lines at the bottom of the panels denote the respective animal presence times for the RO- and RC-scenario.

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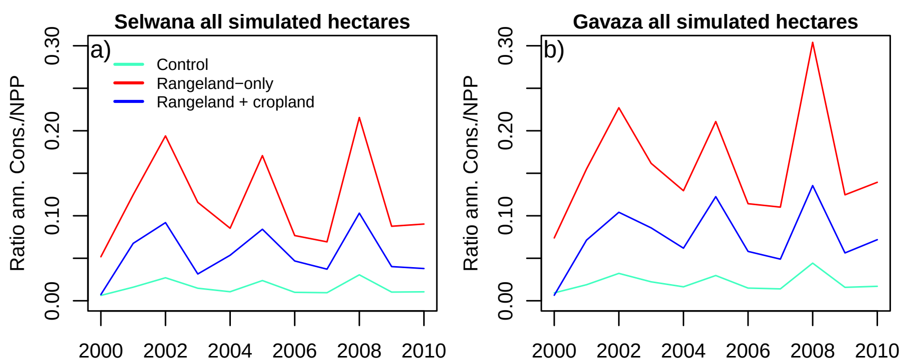

Figure 9. Temporal dynamics of consumption/NPP ratio, integrated across all simulated hectares per site.