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

Mirjam Pfeiffer[1], Munir P. Hoffmann[2], Simon Scheiter[1], William Nelson[3], Johannes Isselstein[4,7], Kingsley Ayisi[5], Jude J. Odhiambo[6], and Reimund Rötter[3,7]

[1]Senckenberg Biodiversity and Climate Research Centre (BiK-F), Senckenberganlage 25, 60438 Frankfurt am Main, Germany
[2]Agvolution GmbH, Phillip-Reis-Str. 2, 37075 Göttingen, Germany
[3]University of Göttingen, Tropical Plant Production and Agrosystems Modelling (TROPAGS), Grisebachstrasse 6, 37077 Göttingen, Germany
[4]University of Göttingen, Grassland Science, Göttingen, Germany
[5]Risk and Vulnerability Science Center, University of Limpopo, South Africa
[6]Department of Plant and Soil Sciences, Faculty of Science, Engineering and Agriculture, University of Venda, South Africa
[7]University of Göttingen, Center of Biodiversity and Sustainable Land Use (CBL), Büsgenweg 1, 37077 Göttingen, Germany

Correspondence: Mirjam Pfeiffer (mirjam.pfeiffer@senckenberg.de)

SUPPLEMENT A

Supplementary tables and figures referenced in the publication.

Table S1. APSIM evaluations specific to aspects relevant to our study. Full references are included in the reference list of the main manuscript.

Topic	Reference
Cowpea	Ncube et al. (2009); Sennhenn et al. (2017)
Groundnut	Hoffmann et al. (2018b)
Maize	Rurinda et al. (2015)
Mucuna	Robertson et al. (2005)
Pearl millet	Akponikpè et al. (2010)
Soybean	Mabapa et al. (2010)
Phosphorus limitations	Delve et al. (2009)
Crop responses to manure application	Probert et al. (2005)
Intercropping systems in southern Africa	Chimonyo et al. (2016)
Residual effects in rotation	Masikati et al. (2014); Ncube et al. (2009); Robertson et al. (2005)

Table S2. Mean and standard deviation of annual GPP across simulated hectares for the years with lowest (left value) and highest (right value) mean value. GL: grassland; WL: woodland; CO: control scenario; RO: rangeland-only scenario; RC: rangeland+cropland scenario.

Site/Area	GL hectares CO	GL hectares RO	GL hectares RC
Selwana	3.13±1.45 to 11.18±4.09	3.11±1.38 to 11.05±4.07	3.14±1.68 to 8.18±2.55
Gabaza A1	3.58±2.24 to 15.79±6.53	3.36±1.92 to 15.78±6.55	2.97±4.41 to 8.93±3.90
Gabaza A2	3.71±1.89 to 13.58±4.39	4.06±2.14 to 13.65±4.52	3.91±2.71 to 8.20±3.36
Gabaza A3	3.56±1.88 to 14.25±3.74	3.64±1.88 to 14.21±3.77	3.59±3.13 to 8.37±3.92
Gabaza A4	3.95±2.32 to 14.54±5.18	3.88±2.35 to 14.48±5.26	3.98±3.38 to 8.79±3.84
Site/Area	**WL hectares CO**	**WL hectares RO**	**WL hectares RC**
Selwana	1.15±0.60 to 3.64±1.71	1.15±0.52 to 3.66±1.67	1.12±1.40 to 2.75±1.41
Gabaza A1	1.52±0.58 to 4.70±1.63	1.69±0.58 to 4.70±1.63	1.55±1.31 to 4.05±1.00
Gabaza A2	1.45±0.56 to 4.44 to 1.30	1.51±0.62 to 4.42±1.29	1.52±0.86 to 3.83±0.87
Gabaza A3	1.30±0.65 to 4.16±1.60	1.41±0.60 to 4.19±1.60	1.31±0.99 to 3.45±0.97
Gabaza A4	1.47±0.73 to 4.34±1.69	1.48±0.56 to 4.38±1.69	1.48±1.29 to 3.68±1.09

Table S3. Mean and standard deviation of annual NPP across simulated hectares for the years with lowest (left value) and highest (right value) mean value. GL: grassland; WL: woodland; CO: control scenario; RO: rangeland-only scenario; RC: rangeland+cropland scenario.

Site/Area	GL hectares CO	GL hectares RO	GL hectares RC
Selwana	1.24±0.46 to 6.02±2.25	1.26±0.44 to 5.97±2.26	1.34±0.87 to 4.33±0.73
Gabaza A1	1.65±1.19 to 8.71±3.79	1.58±0.97 to 8.77±3.79	1.78±2.16 to 4.78±2.42
Gabaza A2	1.53±0.82 to 7.35±2.58	1.68±0.89 to 7.44±2.65	1.50±1.89 to 4.45±1.95
Gabaza A3	1.44±0.64 to 7.79±2.32	1.53±0.65 to 7.82±2.37	1.52±1.89 to 4.60±2.38
Gabaza A4	1.52±1.05 to 7.92±3.16	1.60±1.03 to 7.91±3.21	1.58±2.10 to 4.75±2.28
Site/Area	**WL hectares CO**	**WL hectares RO**	**WL hectares RC**
Selwana	0.40±0.26 to 1.94±0.93	0.42±0.21 to 1.97±0.91	0.41±0.76 to 1.47±0.73
Gabaza A1	0.55±0.24 to 2.59±0.91	0.67±0.24 to 2.62±0.90	0.58±0.72 to 2.20±0.58
Gabaza A2	0.55±0.27 to 2.44±0.75	0.63±0.27 to 2.45±0.74	0.60±0.58 to 2.09±0.49
Gabaza A3	0.48±0.25 to 2.28±0.88	0.54±0.26 to 2.32±0.88	0.51±0.67 to 1.89±0.55
Gabaza A4	0.55±0.27 to 2.39±0.94	0.56±0.26 to 2.42±0.94	0.56±0.69 to 2.01±0.61

Table S4. Average and standard deviations of annual GPP per unit living biomass across simulated hectares for the years with lowest (left value) and highest (right value) mean value. GL: grassland; WL: woodland; CO.: control scenario; RO: rangeland-only scenario; RC: cropland+rangeland scenario.

Site/Area	GL hectares CO	GL hectares RO	GL hectares RC
Selwana	8.42±0.77 to 12.53 ±0.69	8.42±0.64 to 12.94 ±0.84	8.33±1.41 to 12.75±0.68
Gabaza A1	7.37±0.99 to 12.82±0.78	7.77±1.40 to 13.52±1.35	7.59±1.11 to 12.44±1.29
Gabaza A2	7.38±0.98 to 12.37±1.41	7.53±1.10 to 12.93±1.49	7.56±1.19 to 12.30±1.11
Gabaza A3	7.37±1.03 to 12.69±0.95	7.49±1.11 to 12.72±1.23	7.36±1.24 to 13.01±1.22
Gabaza A4	7.32±0.84 to 12.66±1.17	7.55±1.15 to 13.23±1.25	7.44±1.22 to 13.01±1.22
Site/Area	WL hectares CO	WL hectares RO / WL hectares RC	
Selwana	8.51±0.50 to 12.31±0.75	8.74±0.64 to 12.73±0.99	8.67±1.13 to 12.44±0.59
Gabaza A1	8.17±0.54 to 12.49±0.97	8.22±0.53 to 12.40±0.99	8.13±0.85 to 12.35±0.46
Gabaza A2	8.22±0.51 to 12.33±0.85	8.37±0.55 to 13.06±1.00	8.22±0.54 to 12.23±0.54
Gabaza A3	8.18±0.66 to 12.53±0.96	8.09±0.60 to 12.37±0.95	8.22±1.01 to 12.67±0.71
Gabaza A4	8.23±0.63 to 12.28±0.78	8.52±0.82 to 13.32±1.44	8.44±0.69 to 12.66±0.76

Table S5. Average and standard deviations of annual NPP per unit living biomass across simulated hectares for the years with lowest (left value) and highest (right value) mean value. GL: grassland; WL: woodland; CO: control scenario; RO: rangeland-only scenario; RC: rangeland+cropland scenario.

Site/Area	GL hectares CO	GL hectares RO	GL hectares RC
Selwana	2.85±0.89 to 6.74±0.63	3.19±3.25 to 7.19±0.57	3.11±0.68 to 6.88±2.77
Gabaza A1	2.94±0.67 to 7.48±0.68	2.98±0.78 to 7.98±1.05	3.00±1.18 to 7.13±1.00
Gabaza A2	2.62±0.74 to 6.90±0.96	2.53±2.31 to 7.39±1.31	2.62±0.78 to 6.96±1.16
Gabaza A3	2.27±2.73 to 7.16±1.08	2.64±1.73 to 7.31±1.30	2.51±0.73 to 7.35±1.08
Gabaza A4	2.39±1.00 to 7.23±1.05	2.60±1.39 to 7.59±1.07	2.49±0.70 to 7.38±3.01
Site/Area	WL hectares CO	WL hectares RO	WL hectares RC
Selwana	3.37±0.75 to 6.55±1.96	3.67±0.75 to 7.09±0.73	3.58±0.64 to 6.80±0.75
Gabaza A1	3.23±0.77 to 7.25±0.73	3.62±0.64 to 7.29±0.76	3.20±0.52 to 7-16±1.44
Gabaza A2	3.51±0.67 to 7.20±0.71	3.72±0.64 to 7.70±0.80	2.97±0.39 to 7.10±1.81
Gabaza A3	3.35±0.81 to 7.21±1.10	3.49±0.78 to 7.21±0.68	3.44±0.45 to 7.48±0.78
Gabaza A4	3.48±0.73 to 7.14±0.67	3.75±0.82 to 7.87±0.86	3.64±0.47 to 7.47±0.79

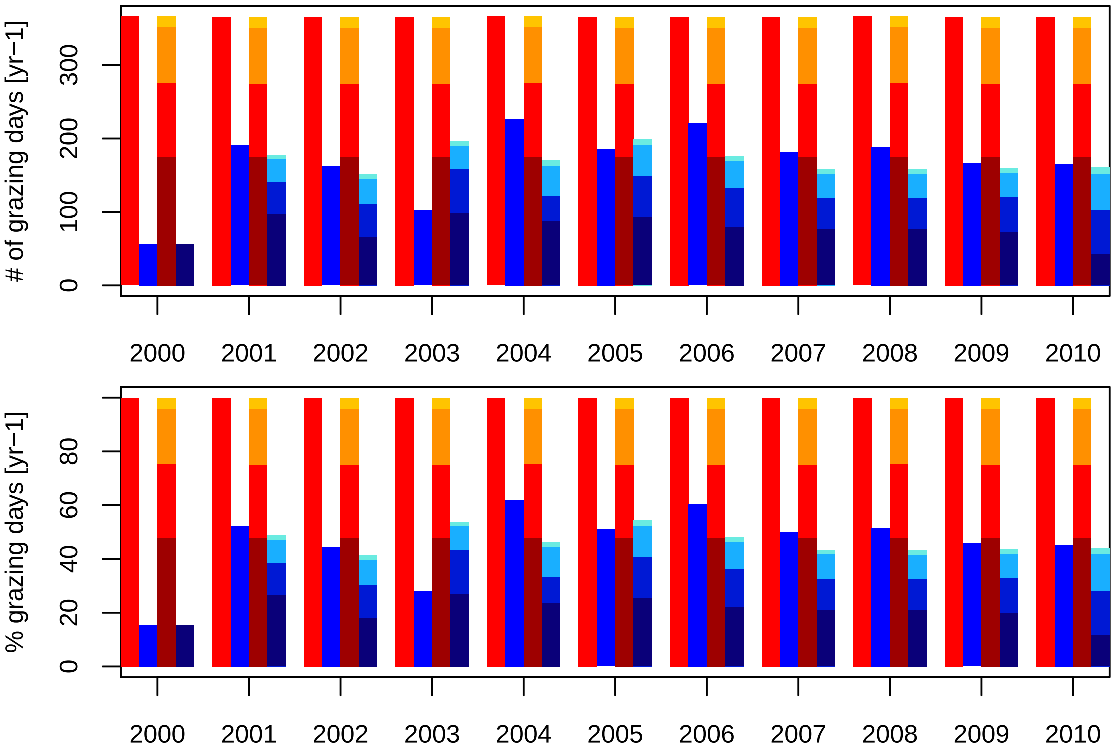

Figure S1. Total number of days spent on rangeland in each year (top panel) and as proportion of the number of days within a year (bottom panel). Red color hues indicate RO-scenario, blue color hues RC-scenario. The left two bars for each year are for Selwana, the right two bars for Gabaza with sub-divisioning according to sub-areas.

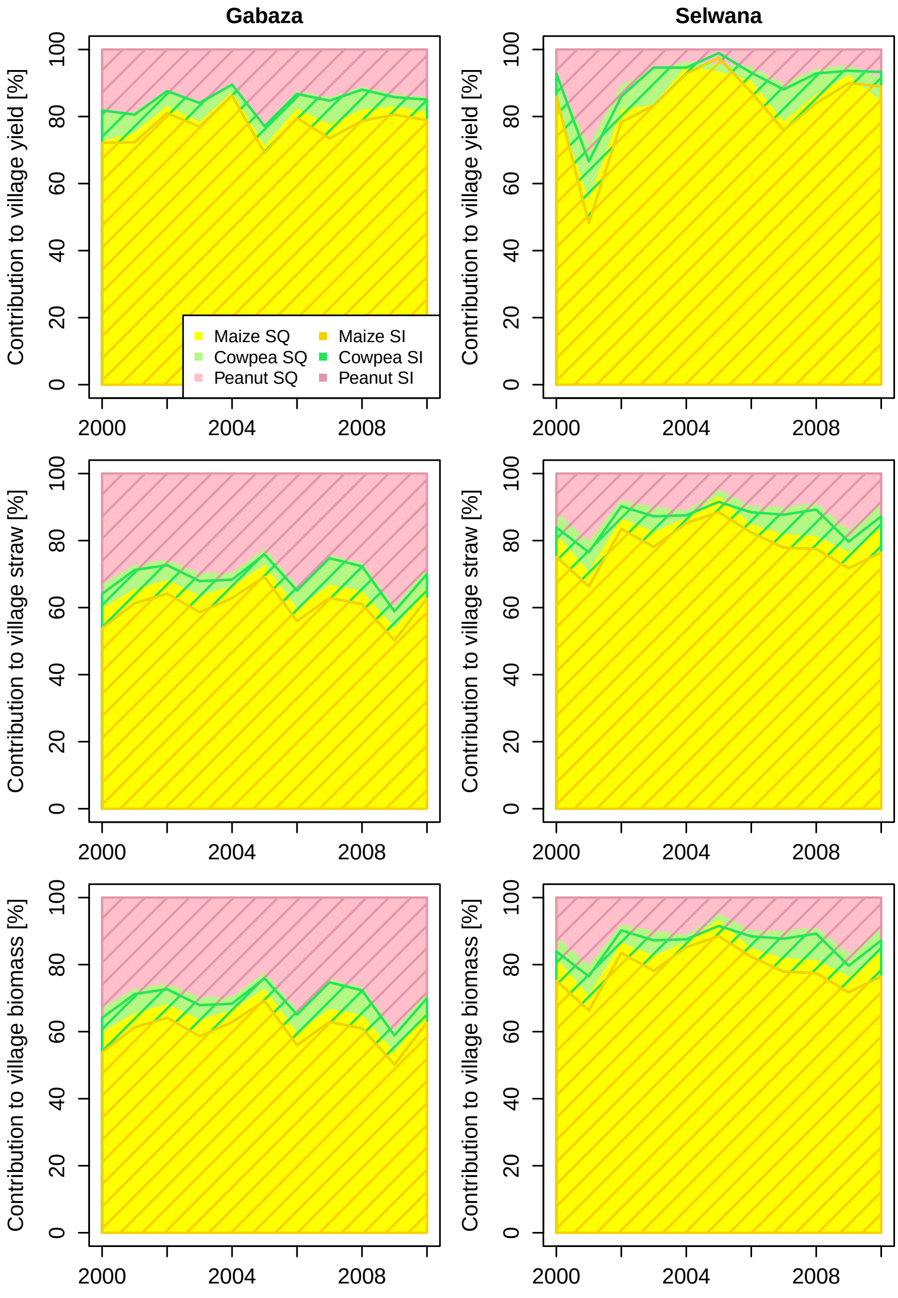

Figure S2. Relative contribution of each crop type to the village total yield, quantity of straw, and total crop biomass (yield+straw). The left column shows the time series for Gabaza, the right column the time series for Selwana. Solid colors indicate contributions to the village-totals for the SQ-scenario, the hatched colors show the contributions in case of the SI-scenario.

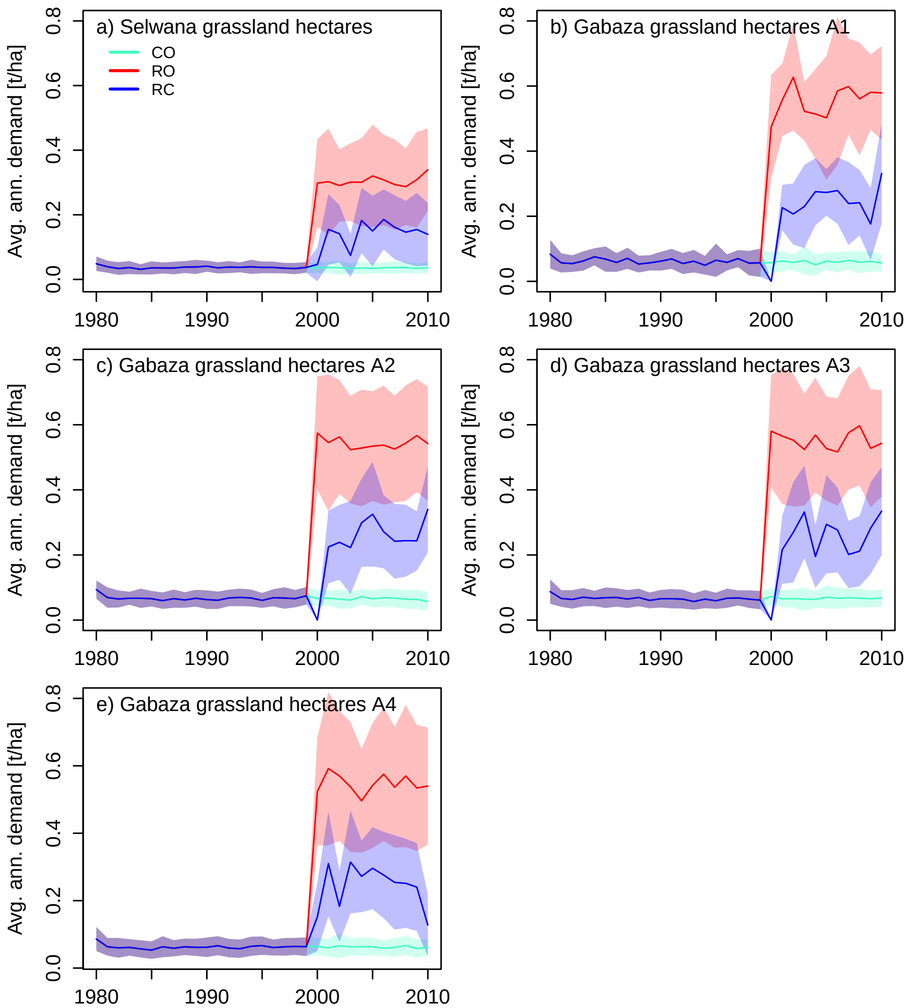

Figure S3. Average per-hectare annual biomass demand across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e).

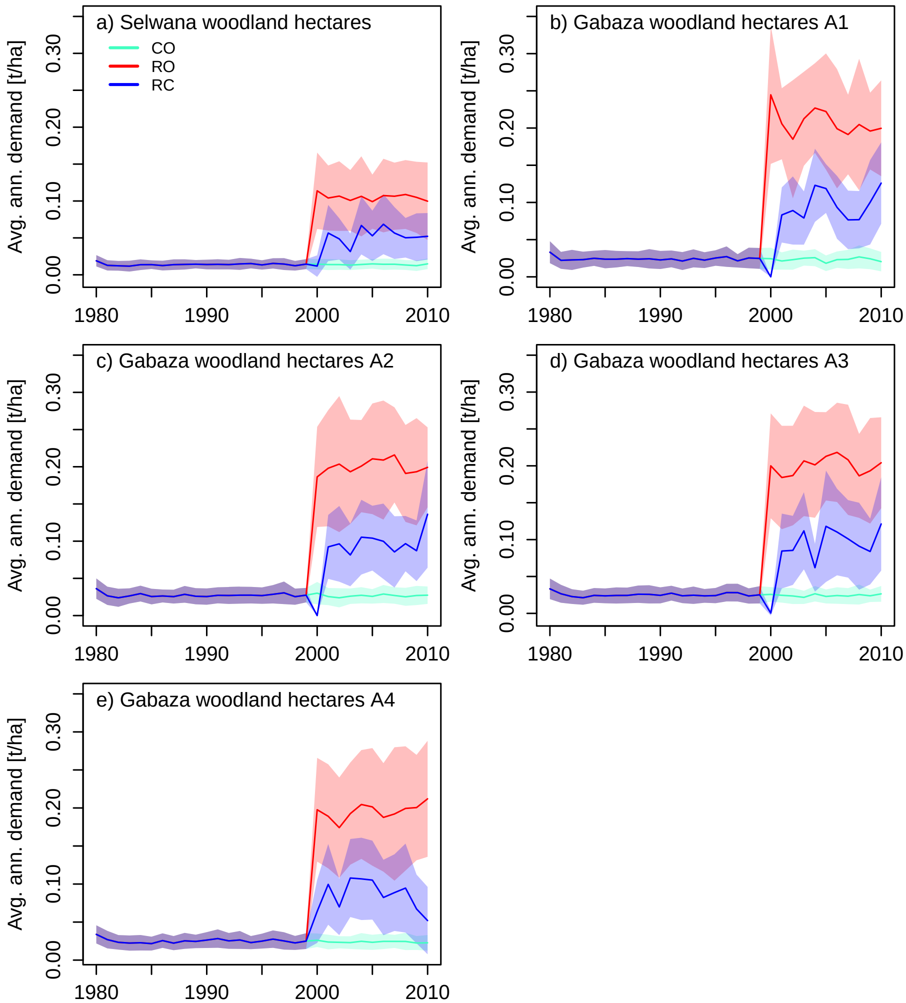

Figure S4. Average per-hectare annual biomass demand across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e).

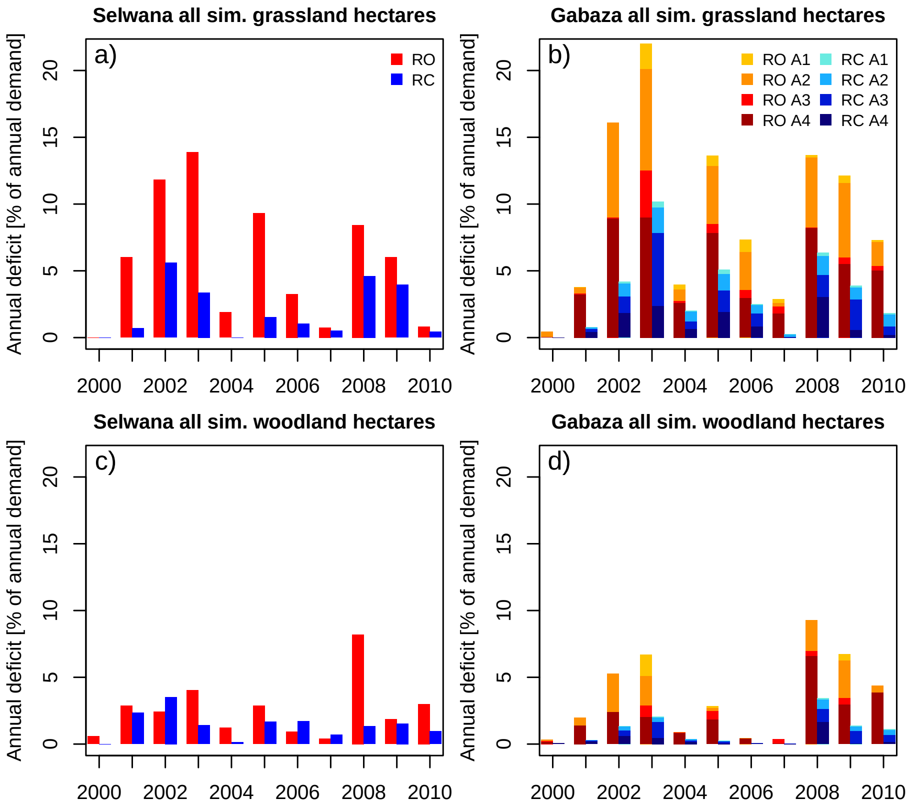

Figure S5. Annual deficit across all simulated hectares per site relative to annual demand across all simulated hectares per site. Panel a) shows relative deficits across all simulated grassland hectares at Selwana, panel b) shows relative deficits for grassland hectares at Gabaza. Panels c) and d) show relative deficits across all woodland hectares for Selwana and Gabaza, respectively. Subdivisions of bars in panel b) and d) indicate the relative contribution of each sub-area to the site-scale annual deficit.

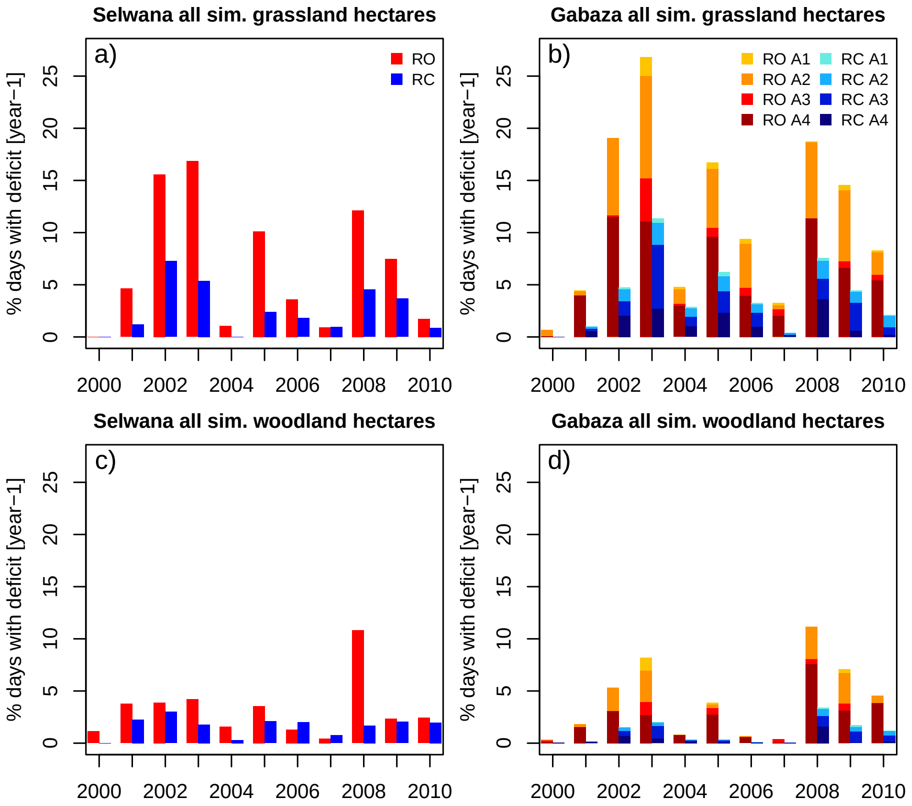

Figure S6. Percentage of grazing days integrated across all simulated hectares that had a deficit, relative to the total grazing days within a year. Panel a) shows percentage of grazing days with deficit across all simulated grassland hectares for Selwana, panel b) shows percentage of days with deficit across all grassland hectares for Gabaza. Panel c) and d) show the same for woodland hectares, respectively. Subdivisions of bars in panel b) and d) indicate the relative contribution of each sub-area to the site-scale percentage.

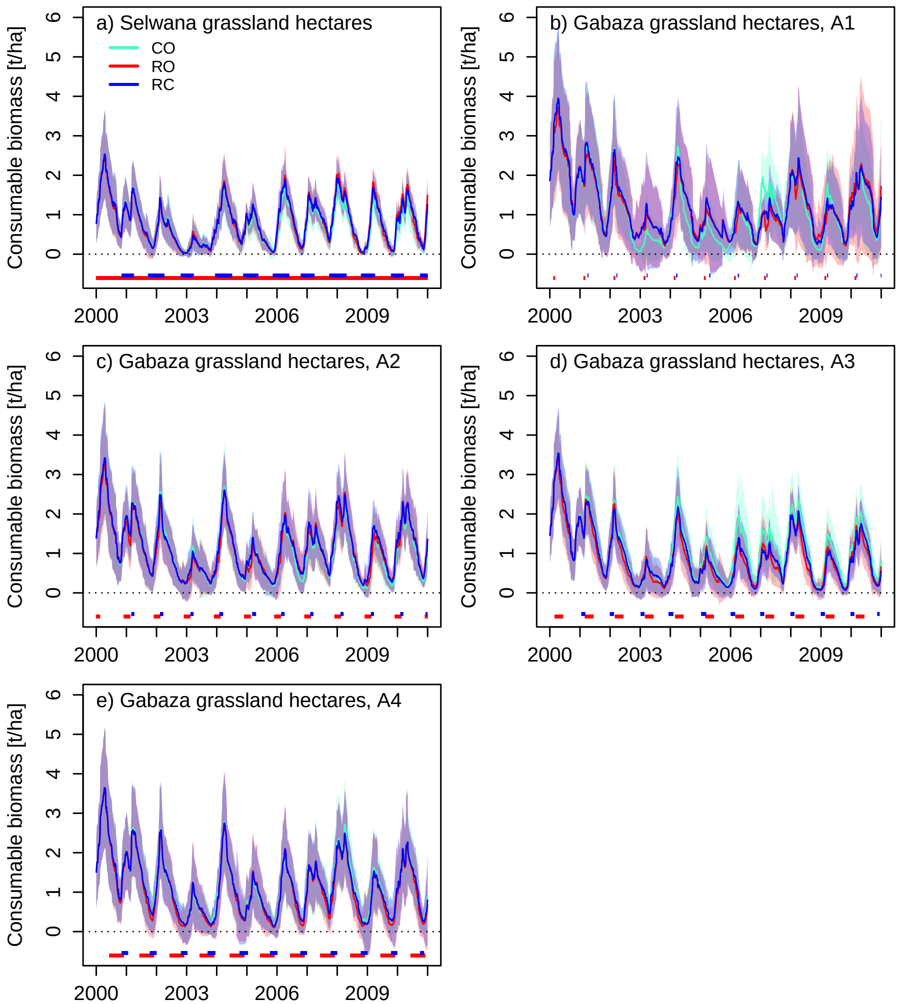

Figure S7. Temporal dynamics of average consumable grass biomass on simulated grassland hectares (living grass leaf biomass + dead standing grass leaf biomass + reproductive biomass, reduced by the minimum amount per hectare that is not available to grazers, i.e., 0.3 t/h for living and dead grass biomass, respectively, and 0.1 t/ha of reproductive biomass) that had no fire in either of the three scenarios up to the day under consideration. Differences between scenarios are therefore exclusively due to the grazing regime. Lines denote the mean across all simulated hectares, shaded areas show the standard deviation.

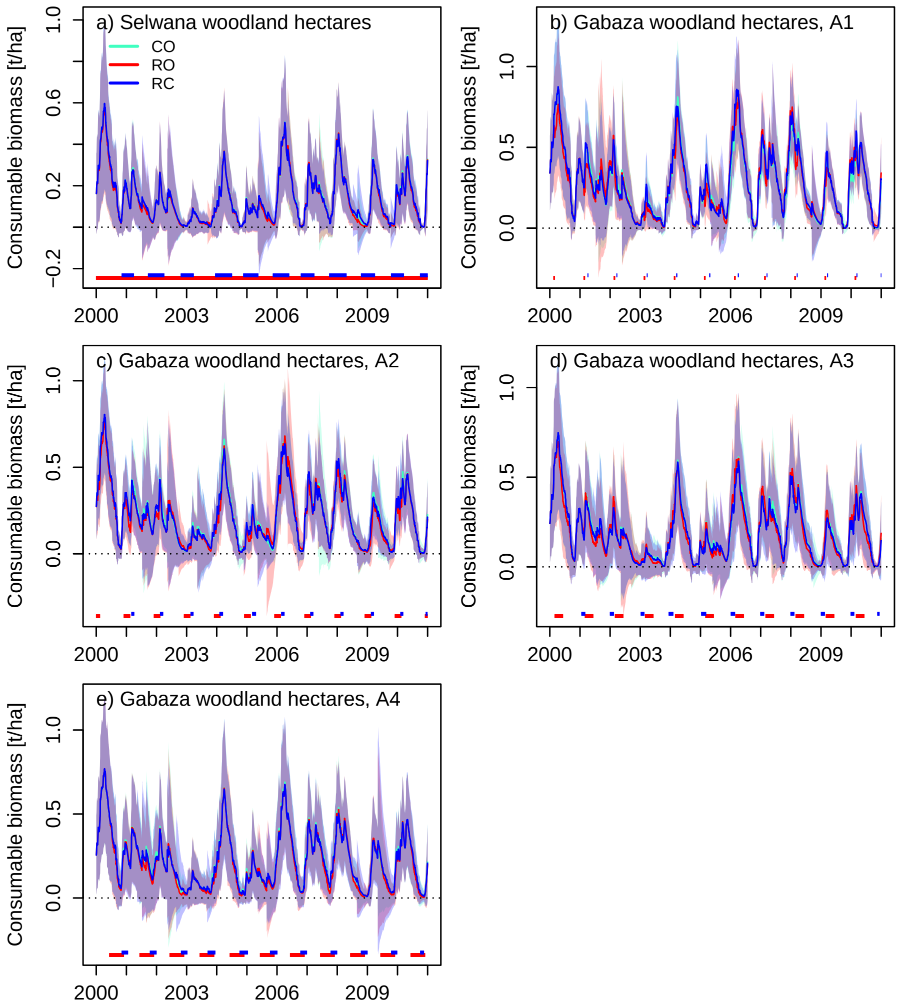

Figure S8. Temporal dynamics of average consumable grass biomass on simulated woodland hectares (living grass leaf biomass + dead standing grass leaf biomass + reproductive biomass, reduced by the minimum amount per hectare that is not available to grazers, i.e., 0.3 t/h for living and dead grass biomass, respectively, and 0.1 t/ha of reproductive biomass) that had no fire in either of the three scenarios up to the day under consideration. Differences between scenarios are therefore exclusively due to the grazing regime. Lines denote the mean across all simulated hectares, shaded areas show the standard deviation.

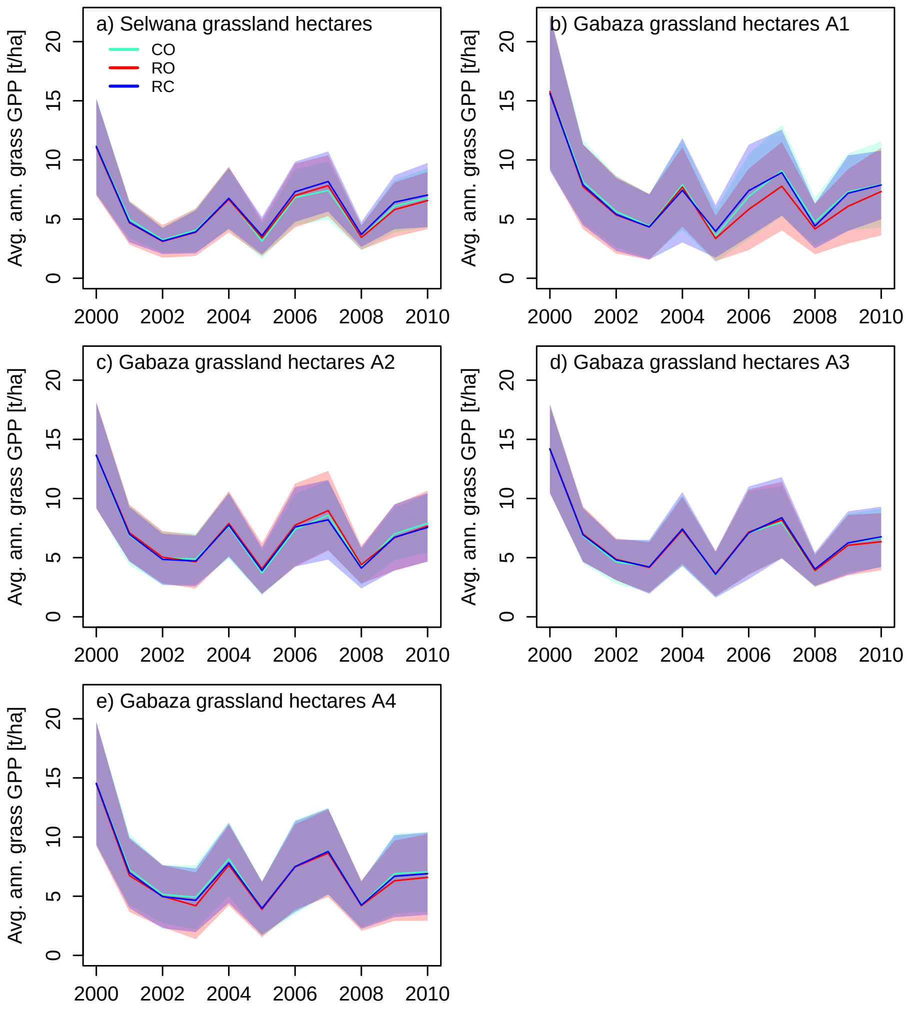

Figure S9. Average per-hectare annual GPP across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Differences between annual mean values between both grazing scenarios and control were all statistically non-significant (two-sided t-test, $p<0.05$).

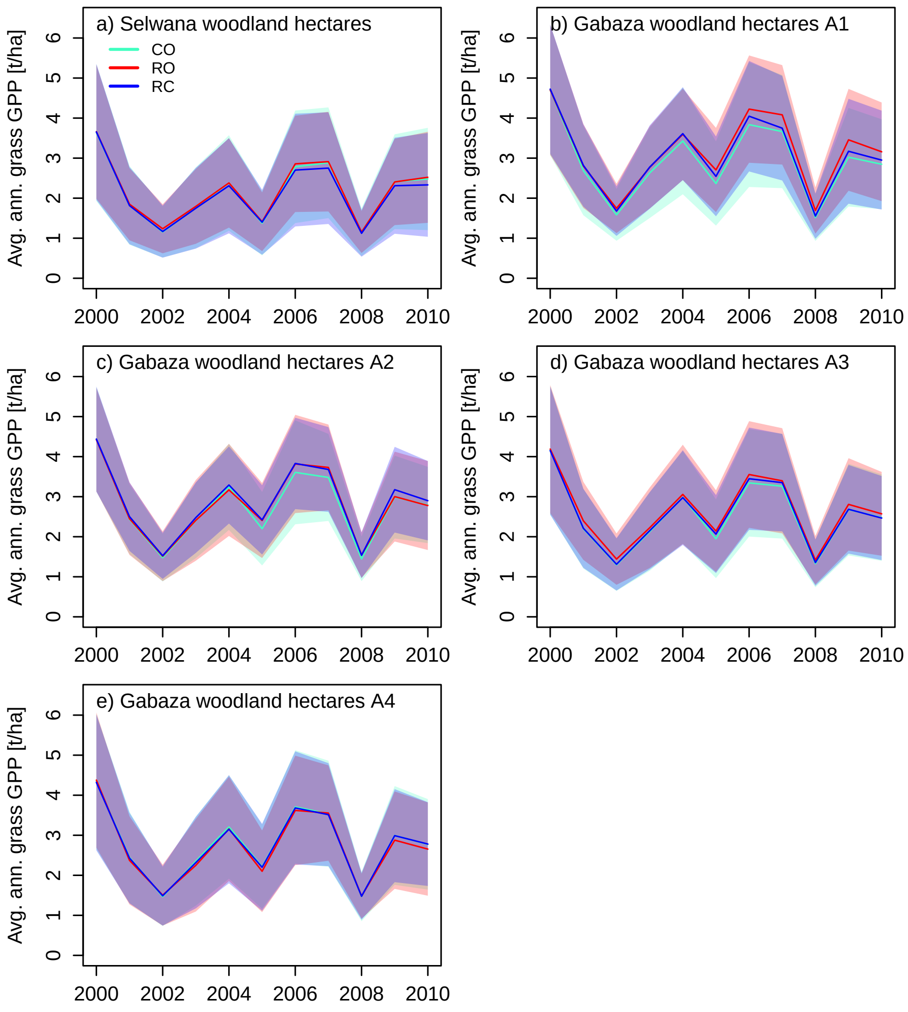

Figure S10. Average per-hectare annual GPP across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Differences between annual mean values between both grazing scenarios and control were all statistically non-significant (two-sided t-test, $p<0.05$).

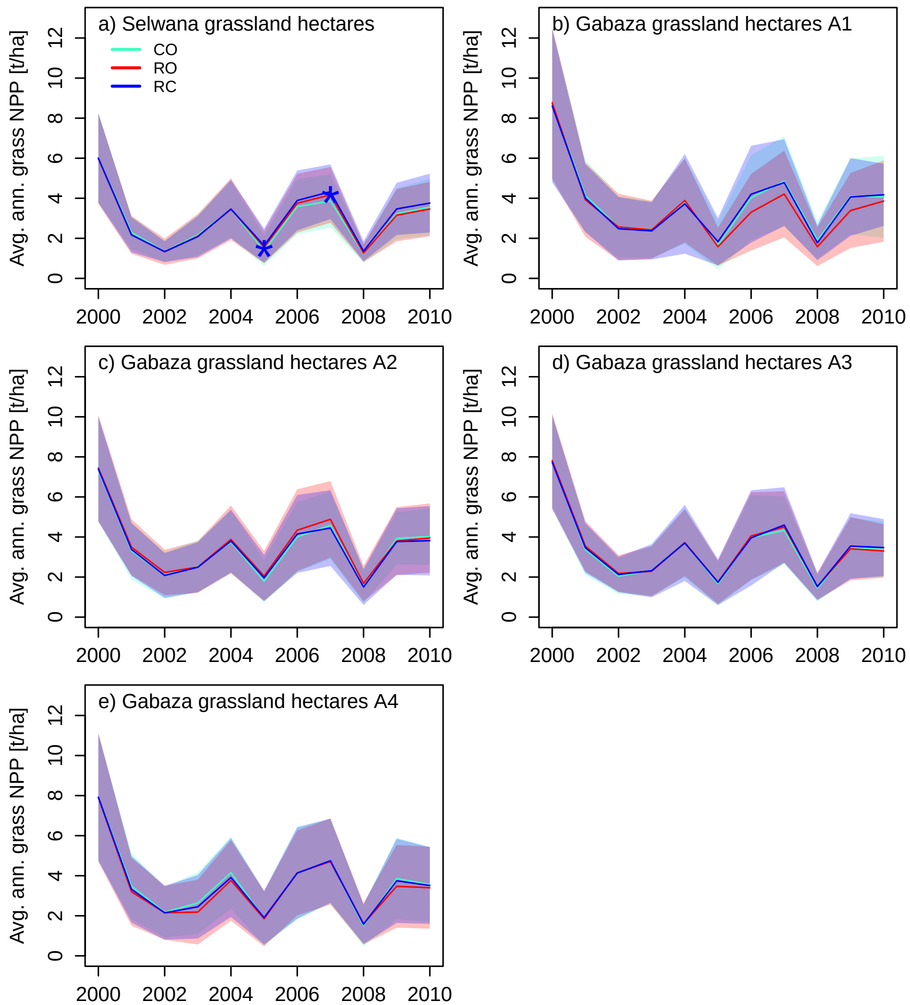

Figure S11. Average per-hectare annual NPP across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values between grazing scenario and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

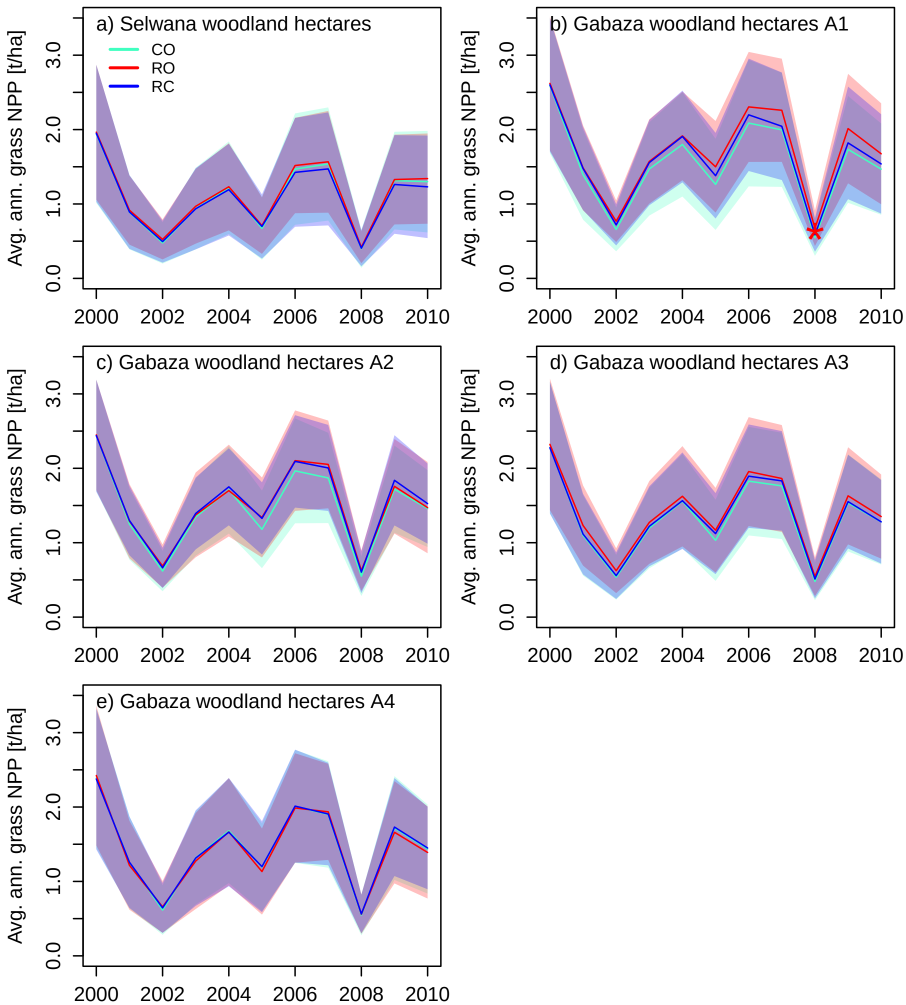

Figure S12. Average per-hectare annual NPP across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values between grazing scenario and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

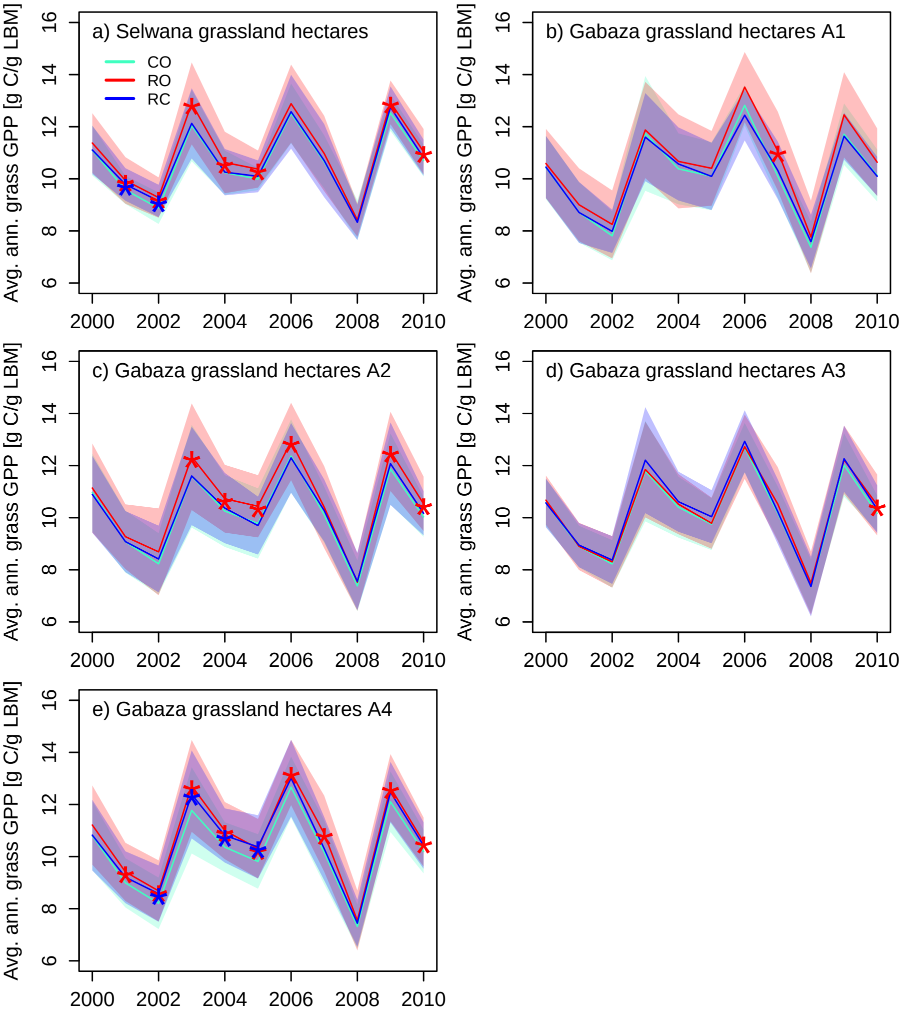

Figure S13. Average annual GPP per unit living grass biomass across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values of grazing scenarios and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

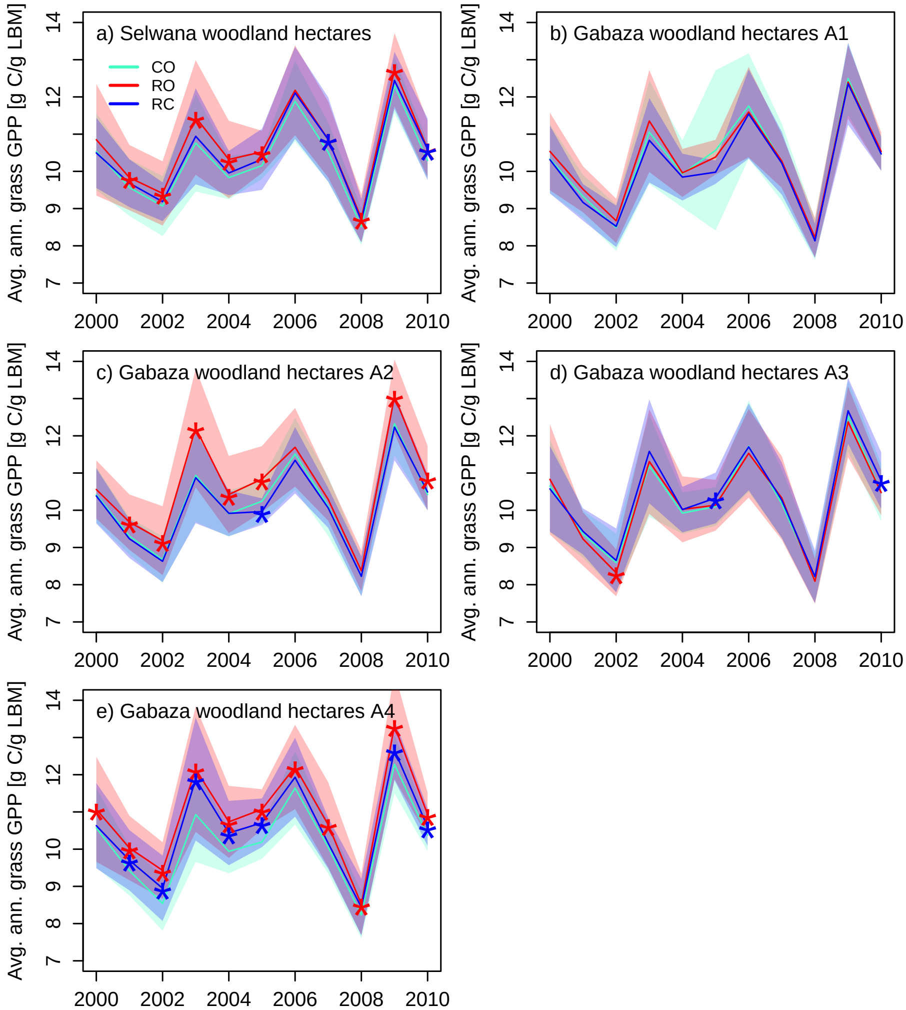

Figure S14. Average annual GPP per unit living grass biomass across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values of grazing scenarios and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

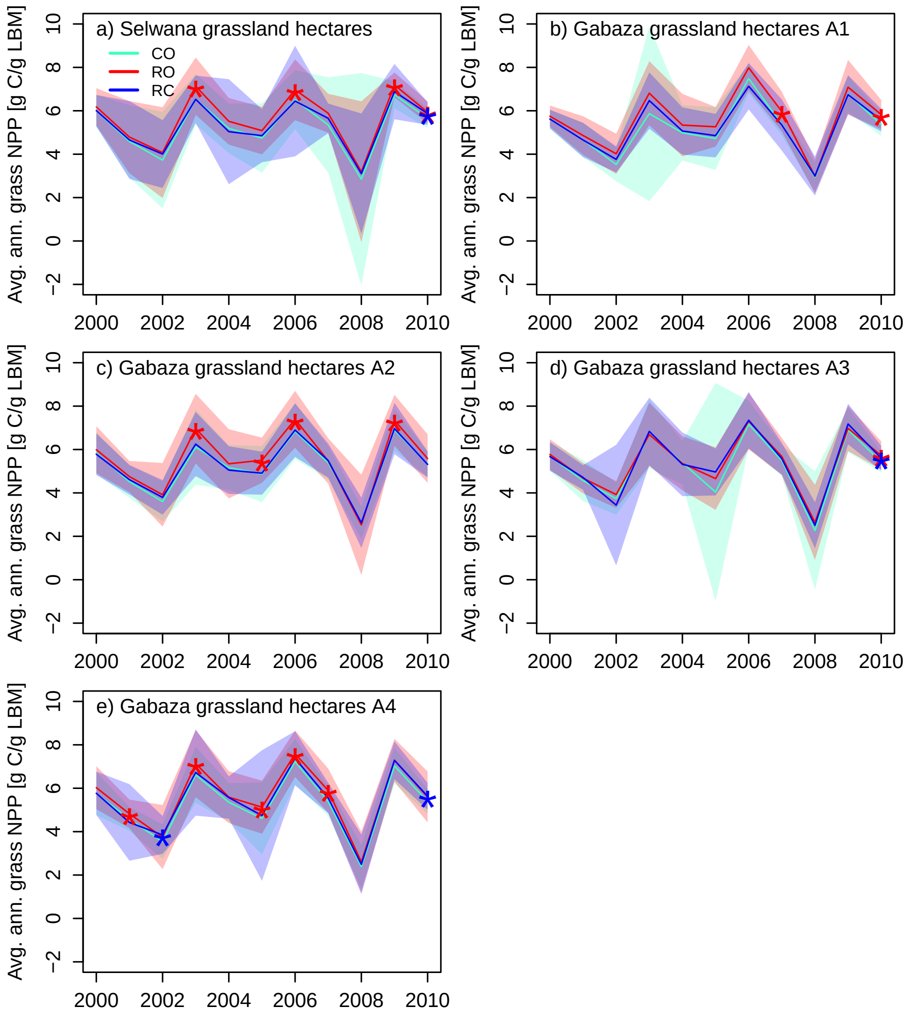

Figure S15. Average annual NPP per unit living grass biomass across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values of grazing scenarios and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

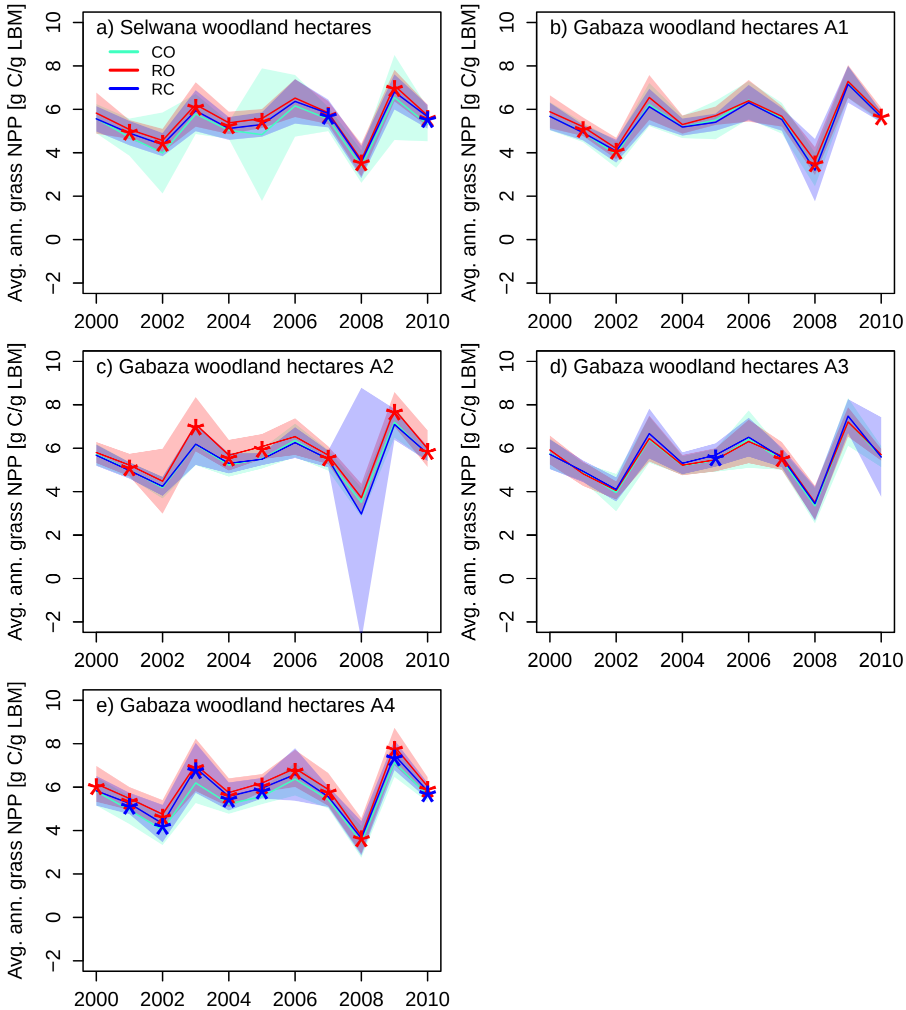

Figure S16. Average annual NPP per unit living grass biomass across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Statistically significant differences between annual mean values of grazing scenarios and control (two-sided t-test, $p<0.05$) are marked with a * symbol.

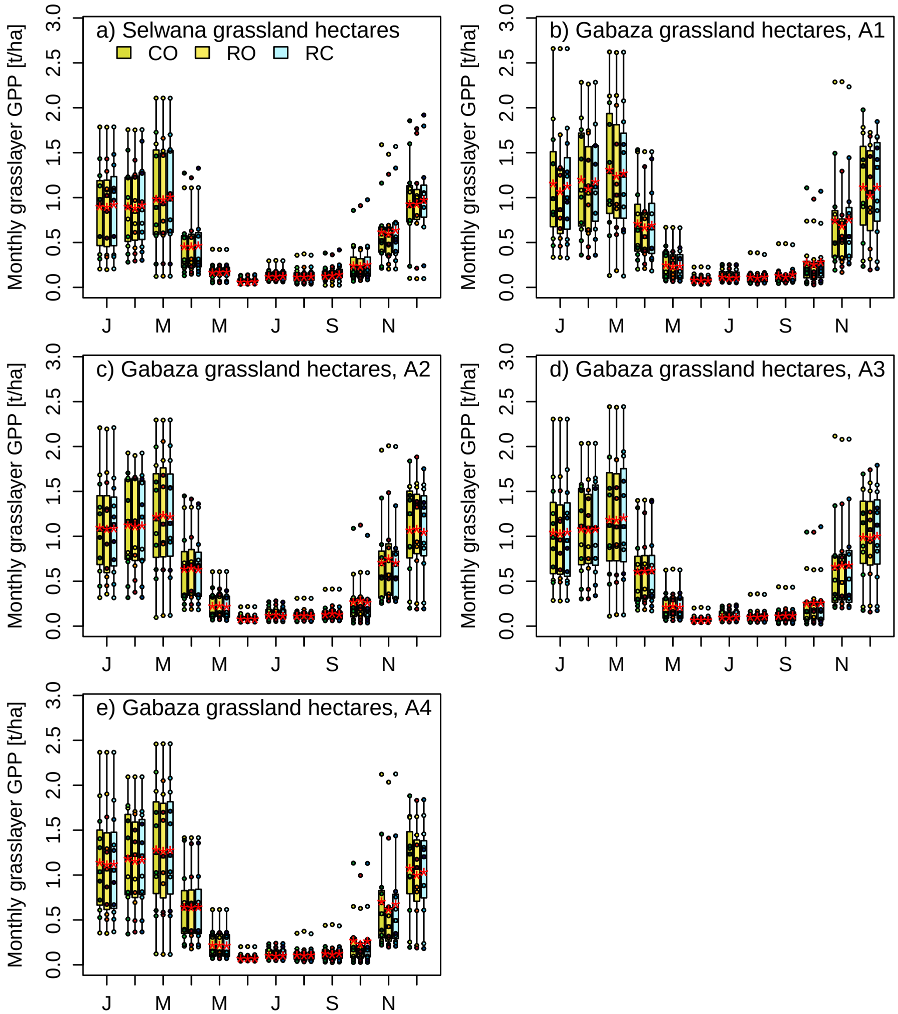

Figure S17. Monthly GPP per hectare across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

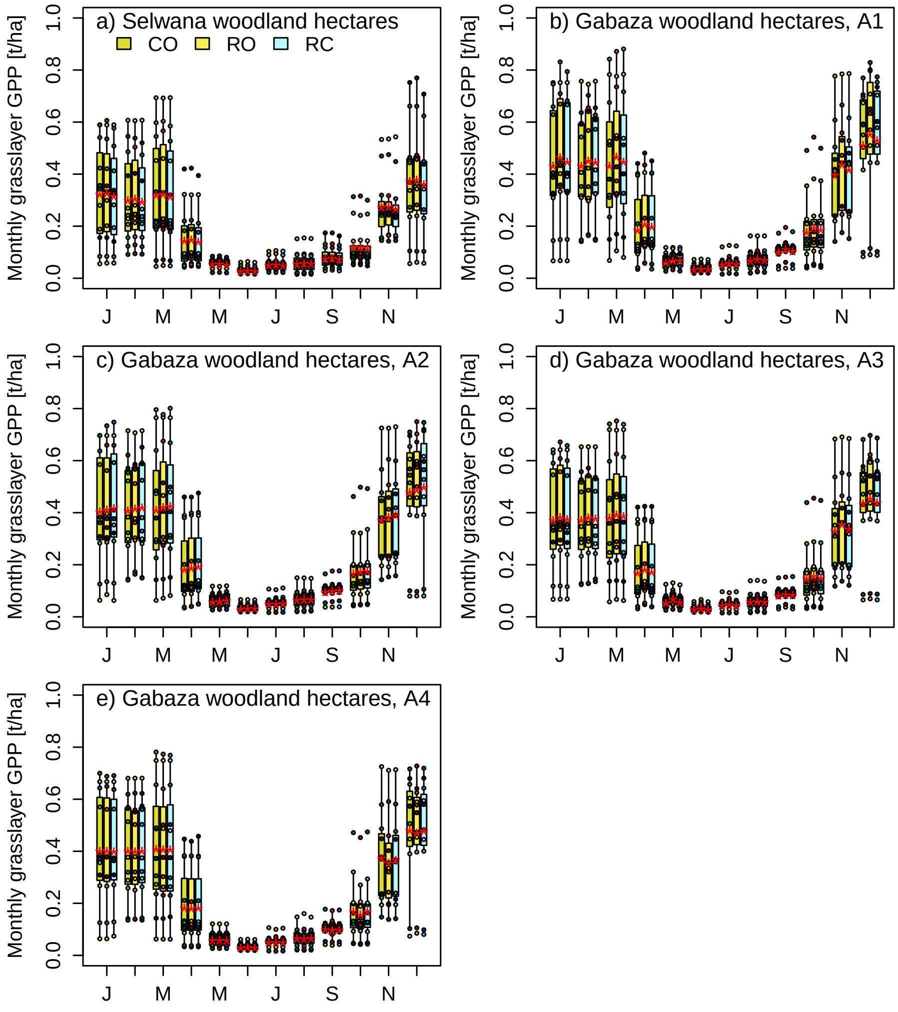

Figure S18. Monthly GPP per hectare across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

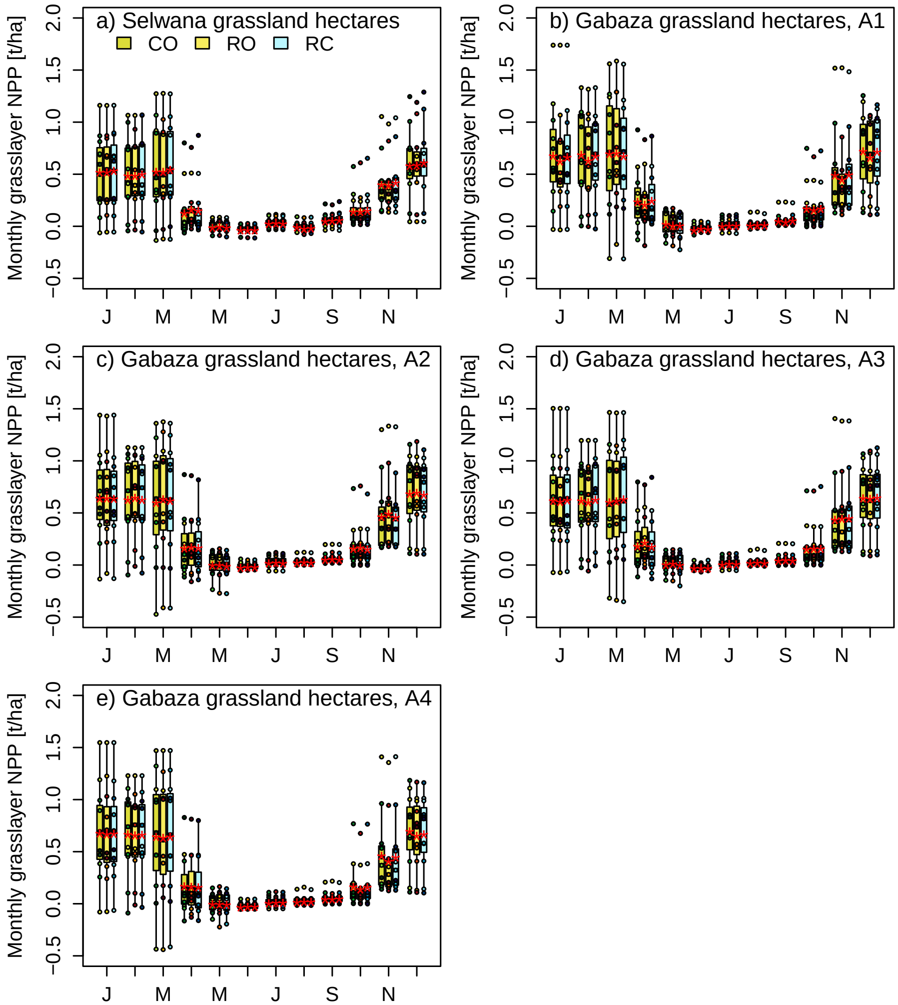

Figure S19. Monthly NPP per hectare across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

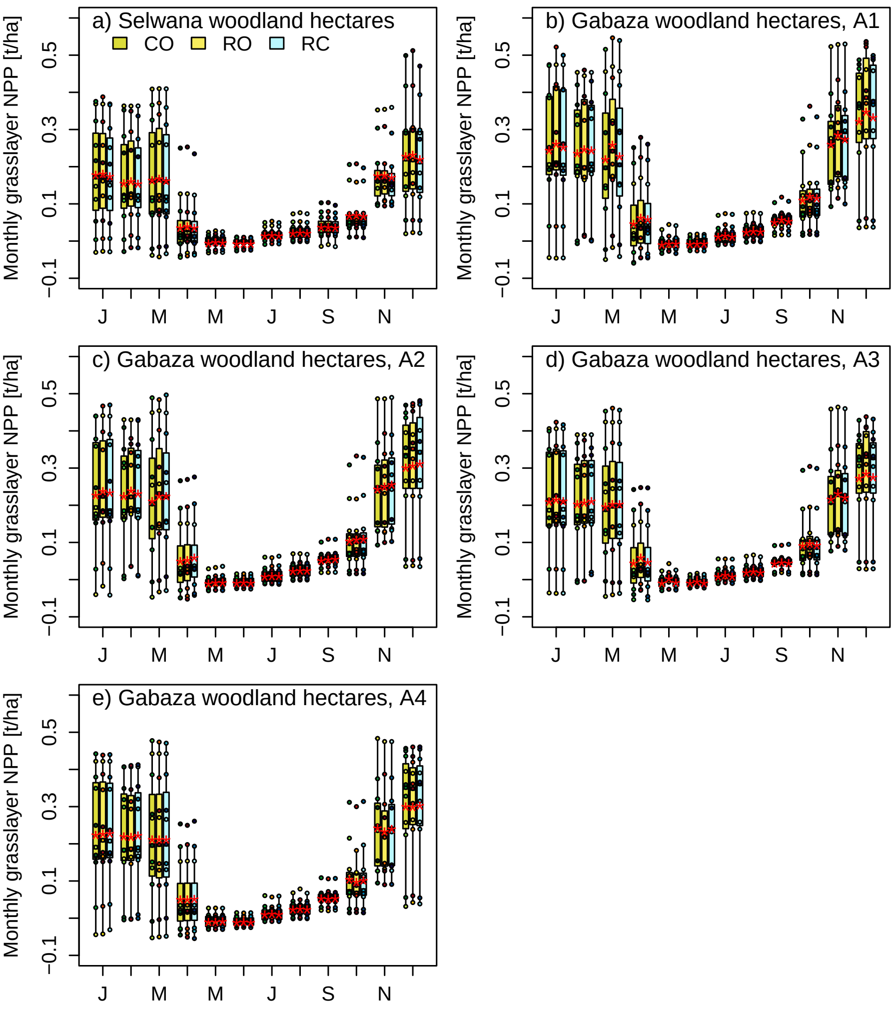

Figure S20. Monthly NPP per hectare across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

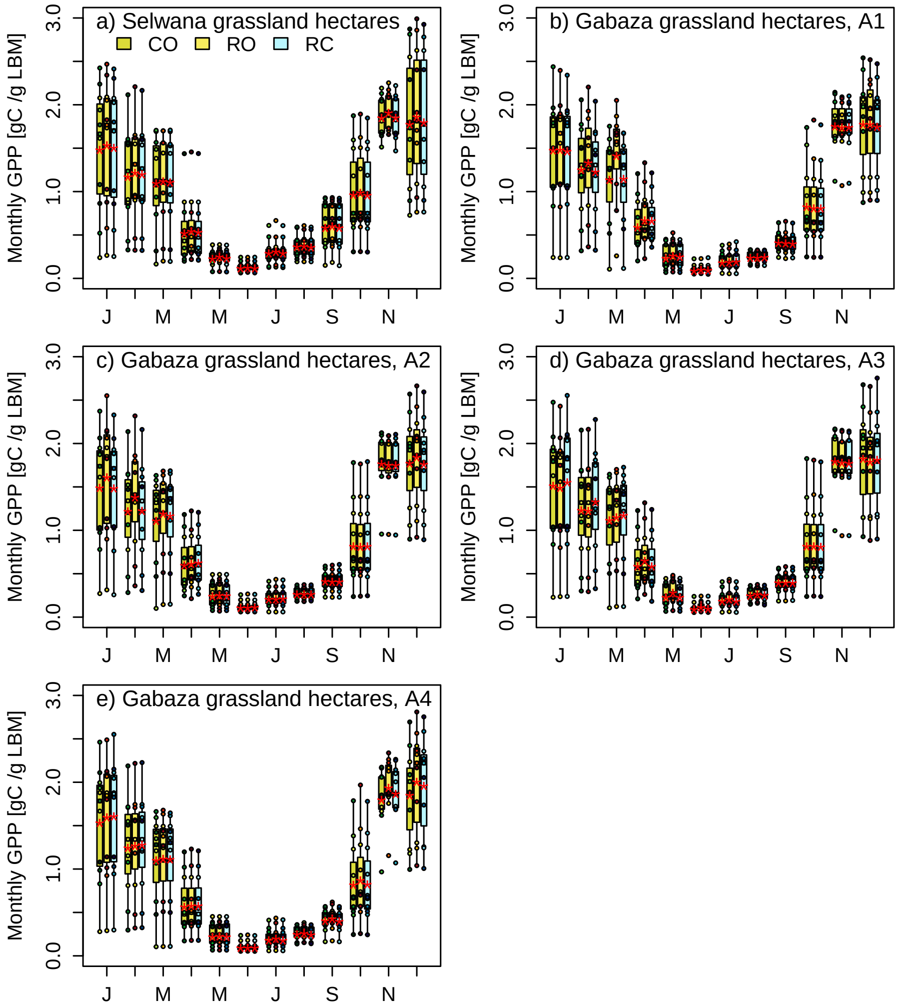

Figure S21. Monthly GPP per unit of living grass leaf biomass across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

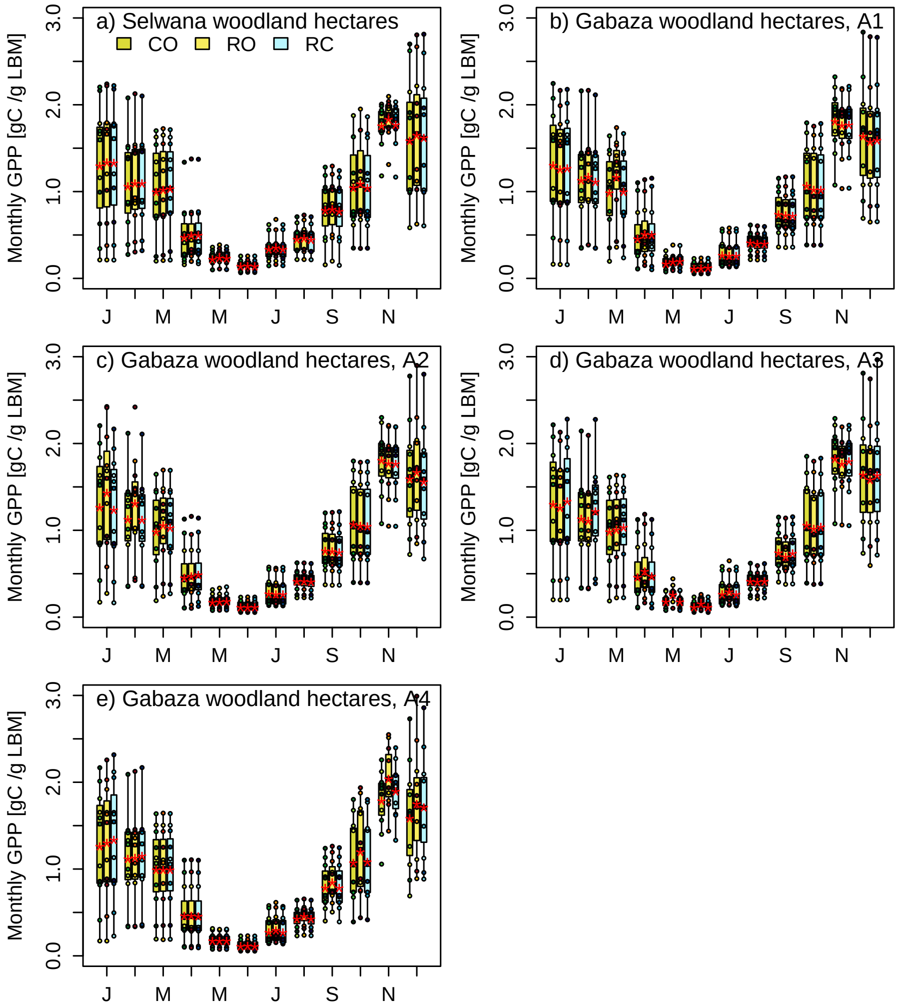

Figure S22. Monthly GPP per unit of living grass leaf biomass across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

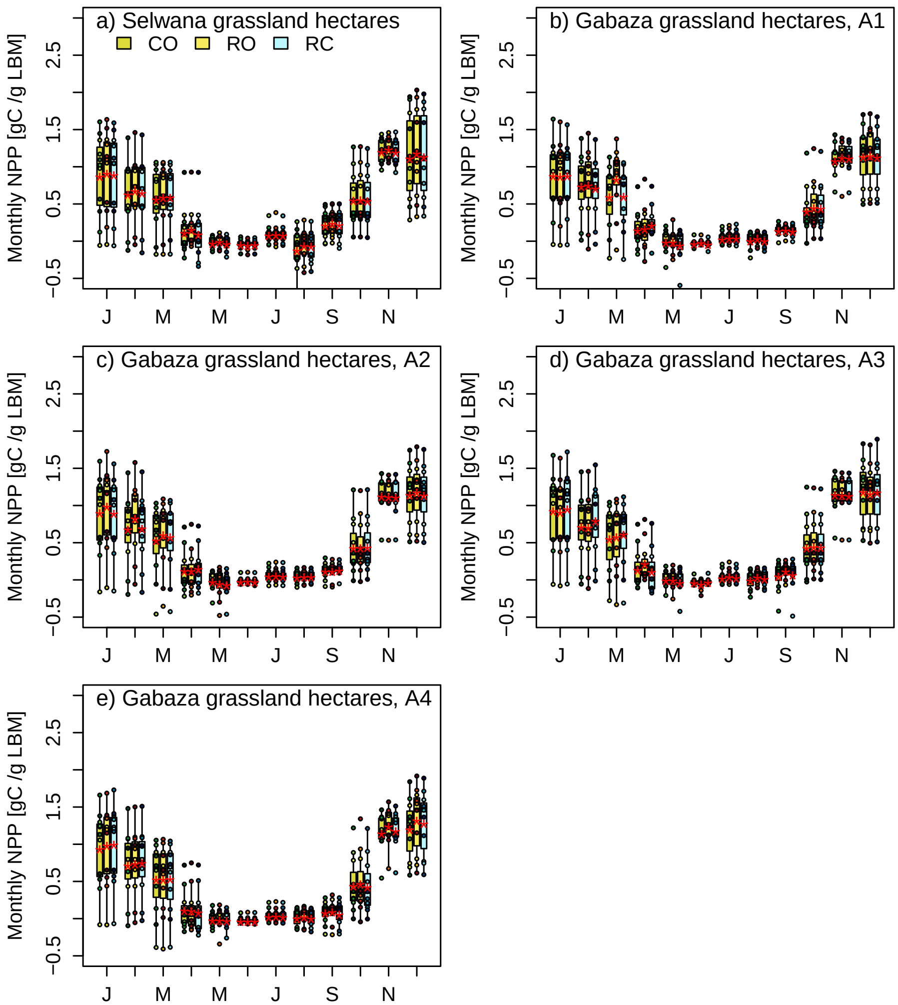

Figure S23. Monthly NPP per unit of living grass leaf biomass across simulated grassland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years.

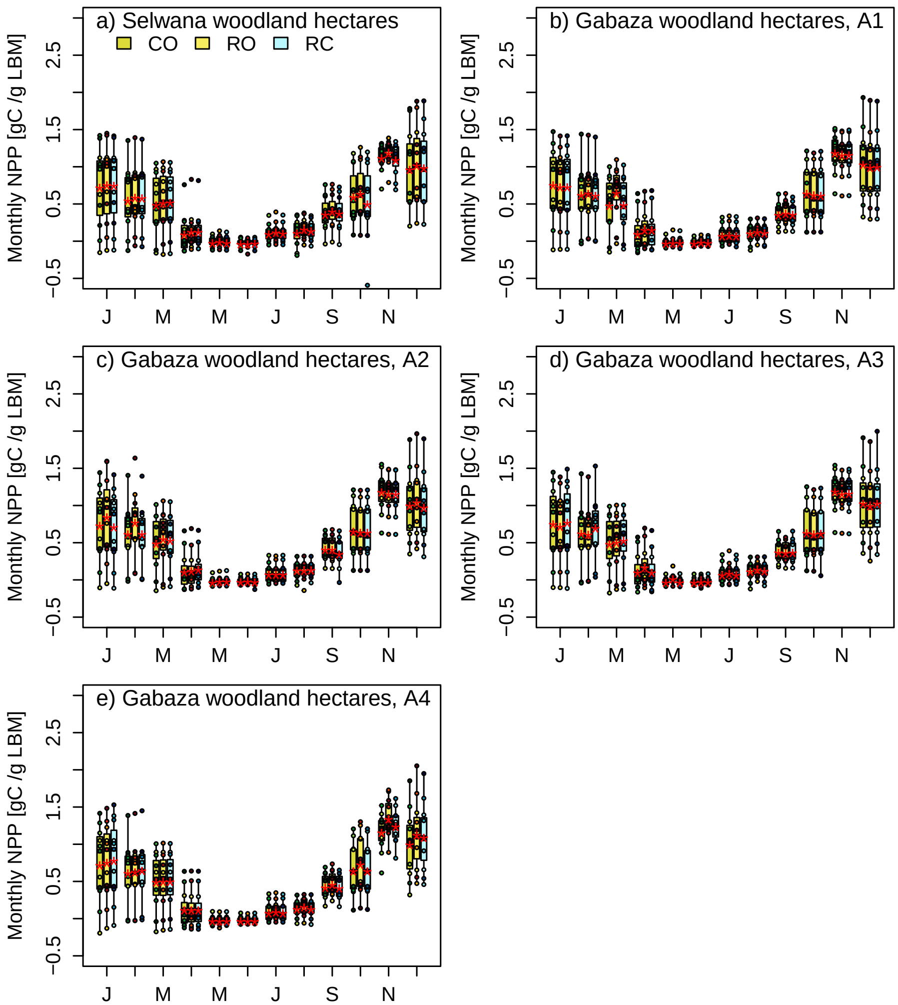

Figure S24. Monthly NPP per unit of living grass leaf biomass across simulated woodland hectares at Selwana (panel a) and the four sub-areas at Gabaza (panel b-e). Different colored boxes mark the three different scenarios (control, rangeland-only, rangeland+cropland grazing), single dots mark the average-across-hectare values of individual years, and red stars mark the average value across all years. .

SUPPLEMENT B

S1. Establishment of grazing sequences for individual hectares of the rangeland area

S1.1 Daily choice of grazing-affected hectares

We assigned an index identifier to each hectare in a given area and attributed it to woodland or grassland based on the respective percentages of both vegetation types (Fig. S25a). Then we determined the hectares affected by grazing on a given day using a two-step decision process that 1) defines the number of affected hectares and then 2) identifies the indices of affected hectares. The number of affected hectares per day (N_{aff}) depends on the distance the herd moves per day. Cattle typically move between 1 and 13 km per day (Schrader, 2007). To link walking distance with the number of visited hectares, we assumed that animals that move from one hectare to another need to cover an average distance of 100 meters (the lateral length of a hectare). Based on the typical range of walking distance combined with the spatial scatter of the herd and lacking more detailed information, we defined a mean of 50 affected hectares per day, with a standard deviation of $\pm$ 20 ha and a lower limit of 10 affected hectares per day. If the available grazing area was smaller than the number of affected hectares per day, animals grazed all available hectares of the area. We drew a random number from a normal distribution using the 50-ha mean and 20-ha standard deviation to determine daily N_{aff} during animal presence periods on a given area. If a random number was < 10 hectares, we discarded it and replaced it with a random-uniform number between 10 and 100 hectares to ensure the lower limit of 10 affected hectares per day. In this way, we created a frequency distribution for the number of visited hectares per day akin to the one shown in Fig. S25b). Knowing N_{aff} for each day in the 11-year simulation period, we then determined the indices of affected hectares (I_{aff}) for each day. We did this via daily random-uniform subsampling from all available hectare indices of the considered area (Fig. S25c), i.e., by randomly choosing N_{aff} random indices from the total number of hectare indices.

S1.2 Daily animal distribution across affected hectares

To distribute the LU over the daily affected hectares I_{aff}, we assume that animals form between 1 and 5 sub-groups, with variable sub-group sizes and spatial densities. Based on a 1-minute temporal resolution, we define animal units (AU) according to the number of minutes per day multiplied by the number of LU per village (i.e., 1440 x 90 = 129000 AU for Gabaza, and 1440 x 87.4 = 125856 AU for Selwana) that we then distributed on the affected hectares I_{aff}. The minute resolution allows consideration of animals spending only part of a day on an individual hectare. For each day, we created between 1 and 5 animal subgroups ($0<N_g<6$) based on a random-uniform distribution (Fig. S25d). We placed the group centers randomly on the number of affected hectares N_{aff} (Fig. S25e illustrates this procedure for an example with 5 sub-groups). For each group, we drew the scatter (i.e., standard deviation) around the group center from a random uniform distribution ranging between 1 and 0.5 times the number of affected hectares (colored horizontal lines in Fig. S25e illustrate the standard deviation, i.e., scatter, the vertical lines the locations of the individual group centers). We chose this spread around the group center somewhat arbitrarily to describe how tightly or loosely the animals within a group stay together. It also influences how strongly one

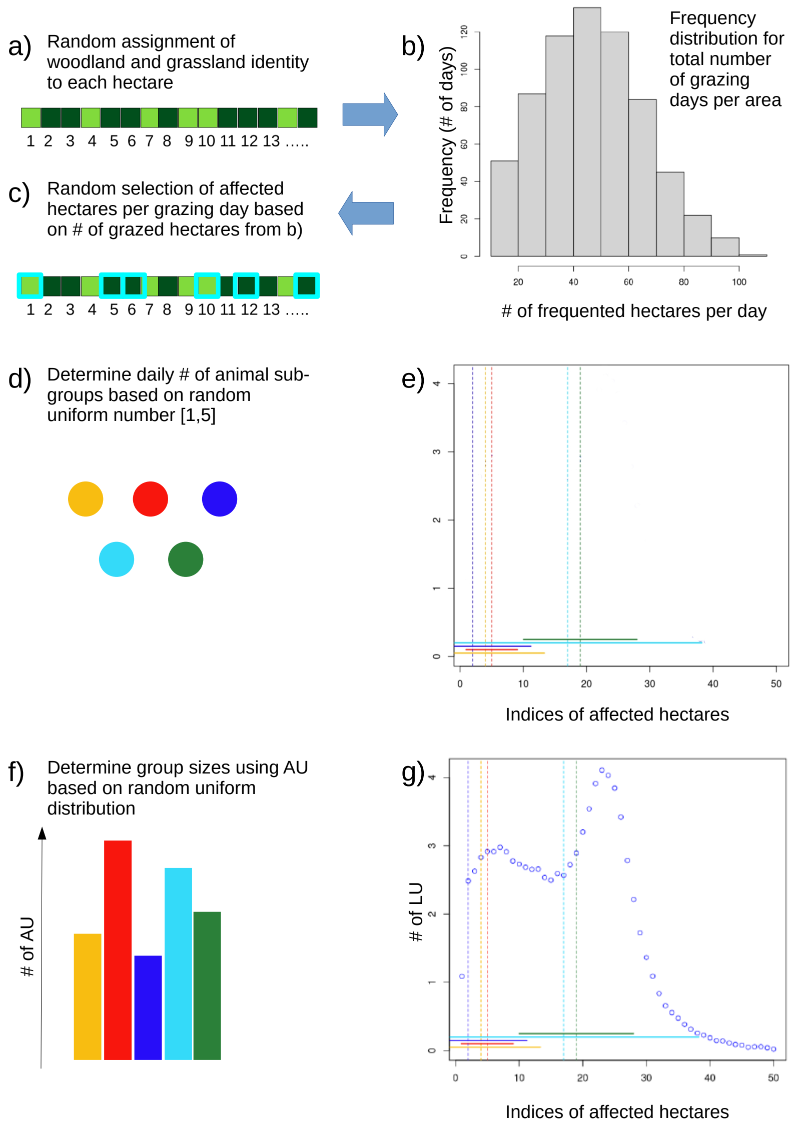

Figure S25. Illustration of the steps involved in creating the hectare-specific grazing sequences. .

subgroup will intermingle with other subgroups on the number of affected hectares. We assigned the AU to the different groups by creating fractional group sizes. For this, we first drew (N_g-1) random uniform numbers between 0 and 1, then size-sorted these to establish the group breaks, and determined the fractional group sizes according to the differences between the breaks (including 0 and 1 as lower and upper edges). The fractional group sizes were then multiplied with the number of AU to obtain the daily AU number per group (Fig. S25f). For each group of AU, we applied a random normal distribution using the group's mean and standard deviation ((group center and scatter, as shown in Fig. S25e) to determine how many AU of each group fall on the hectares around the one representing the group mean. We iteratively re-distributed AU whose drawn numbers were <1 or $>N_{aff}$.

Generating individual random normal distributions for varying numbers of animal groups of variable size allows flexible animal distribution on the affected hectares. The overall distribution of all animals in the herd emerges from the overlay of the individual normal distributions (Fig. S25g). The described approach thus allows the creation of flexible multi-modal distributions of livestock. It imitates the daily group dynamics of livestock in a pseudo-explicit manner that does not require exact knowledge of spatial relationships between affected hectares while still creating average long-term characteristics of herd behavior. When assigning the AU to the affected hectares, we randomly assigned the lower range of AU numbers to the woodland and the higher quantities of AU to the grassland hectares to consider the higher feed availability on grassland than woodland. For use in aDGVM2, we reconverted the daily assigned AU for each affected hectare to daily LU per hectare (Fig. S25g).