Sustainable agricultural intensification mitigates but cannot prevent soil carbon losses under climate change: A DayCent model approach.

Drylands are among the ecosystems most exposed to climate change worldwide. Arid, semi-arid, and dry sub-humid regions are defined by restricted water availability, pronounced climate variability, and soils that are often highly susceptible to degradation. Because of these characteristics, changes in temperature and rainfall regimes can rapidly alter ecological functioning and agricultural performance in such environments (Huang et al., 2016; 2017a; Koutroulis, 2019). Global assessments indicate that warming has progressed more rapidly in drylands than in humid regions, and projections further suggest that dryland areas may continue expanding during this century. In Brazil, drylands occupy about 1.18 million km² and include extensive farming areas that are already under pressure from recurrent droughts and increasing aridity (Sudene, 2021; Greschuk et al., 2025; Tomasella et al., 2025).

Agriculture and land-use change are central to Brazil's greenhouse gas balance, representing more than 70% of annual emissions (Albuquerque et al., 2020; Dias et al., 2016). In dryland regions, especially in the Caatinga, the conversion of native vegetation to cropland or pasture has frequently reduced the return of organic residues to the soil while accelerating soil organic matter decomposition. As a result, SOC stocks tend to decline, which compromises fertility, productivity, and several ecosystem services. In the Brazilian semi-arid region, conventional cropping systems have already been associated with substantial SOC depletion when compared with native vegetation, reinforcing the need for management strategies capable of maintaining or increasing soil carbon under agricultural use (Medeiros et al., 2020; IPCC, 2022; Tariq et al., 2024).

Integrated agricultural systems (IASs), particularly crop-livestock integration (CLI) and crop-livestock-forestry integration (CLFI), have been proposed as promising pathways to improve dryland sustainability. By combining agricultural, forage, livestock, and sometimes tree components in the same area, these systems may enhance residue inputs, nutrient cycling, soil aggregation, and microbial functioning. Previous field studies have reported positive effects of IASs on SOC, N, and biological attributes of soil, but evidence remains limited regarding their long-term performance under future climate change in Brazilian drylands (Almeida et al., 2021; Maia et al., 2022; Soares et al., 2019; Tonucci et al., 2023).

Investigating this question requires tools that move beyond short-term field snapshots. Process-based ecosystem models are particularly useful because they simulate the interaction among climate, soil, vegetation, and management over time. The DayCent model is one of the most widely used tools for this purpose, allowing simulation of C, N, P, and S dynamics in managed ecosystems on a daily time step (Parton et al., 1998; Del Grosso et al., 2012). Although Century-based approaches have been applied previously in Brazilian drylands, long-term evaluations that explicitly combine management scenarios with future climate forcing are still scarce, and the use of DayCent in this context remains novel (Althoff et al., 2018; Araújo Neto et al., 2021; Primo et al., 2023).

Accordingly, this study applied DayCent to simulate SOC and N dynamics from 2024 to 2100 under contrasting management intensities in three representative Brazilian dryland regions: Betânia do Piauí (PI), Petrolina (PE), and Sobral (CE). These areas encompass different soil textures, climatic conditions, and agricultural systems, including native vegetation, conventional systems, and intensified CLI and CLFI arrangements. After calibrating and validating the model with SOC and N stocks from the 0-30 cm layer, we evaluated the effect of current and alternative management strategies under present climate and under SSP2-4.5 and SSP5-8.5. We hypothesized that: (i) intensified management, especially fertilization combined with no-tillage, would increase SOC relative to conventional systems under the current climate; (ii) future climate change would intensify SOC losses, particularly in coarse-textured soils; and (iii) integrated systems would display greater resilience and partly attenuate climate-driven declines in SOC.

Methodology

Study area and agricultural management description

The study was carried out in three agricultural areas located in the Brazilian drylands (Fig. 1): Petrolina, Pernambuco; Betânia do Piauí, Piauí; and Sobral, Ceará. Petrolina (09°03′ S, 40°19′ W; 389 m a.s.l.) is characterized by an Ultisol and a mean annual temperature and rainfall of 26.9 °C and 440.9 mm, respectively, with rainfall concentrated mainly from November to April. Betânia do Piauí (08°09′ S, 40°46′ W; 480 m a.s.l.) is also located on an Ultisol, but includes both sandy and clayey soil conditions. Sobral (03°41′ S, 40°20′ W; 69 m a.s.l.) has a Haplic Inceptisol. According to Köppen classification, all three sites fall within the hot semi-arid BSh climate zone (Alvares et al., 2013; INMET, 2025; Soil Survey Staff, 2014).

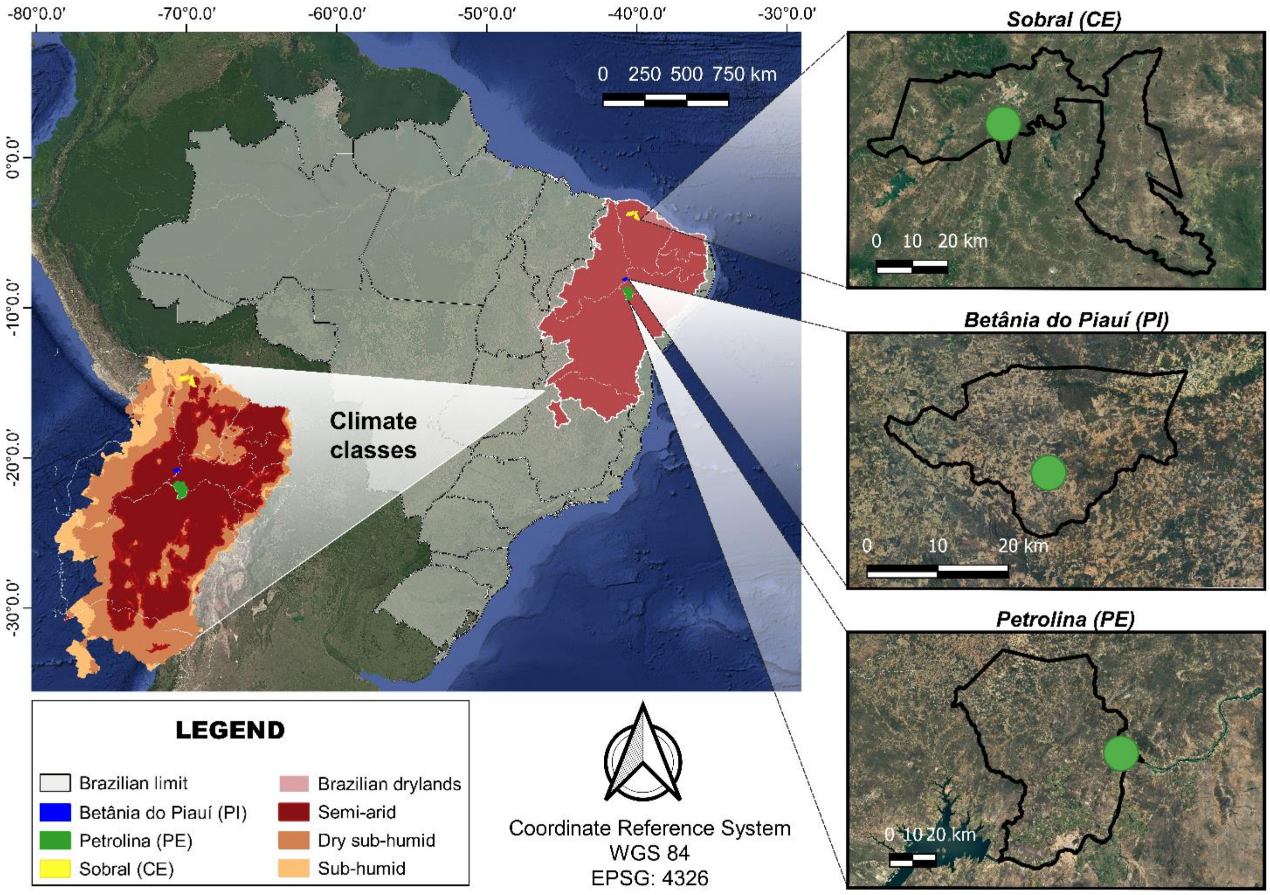


Fig. 1. Geographic position of the three study areas within Brazilian drylands and their corresponding climate classes.

In Petrolina, three land uses were represented: native vegetation (NV), native vegetation moderately grazed by goats during the rainy season since 1990, and buffel grass pasture established in 1990 after conversion from native vegetation. Grazing intensity in both the grazed native vegetation and pasture systems corresponded to 0.6 AU ha^{-1}. At the time of sampling, the pasture showed no clear signs of degradation. In Betânia do Piauí, four land-use situations were examined across two soil textures. In the clayey Ultisol, native vegetation and a CLI system established in 2021 by direct conversion from native vegetation were evaluated. The CLI was based on sorghum intercropped with buffel grass during the rainy season for silage production, followed by moderate sheep grazing during the dry season. The same management sequence was adopted in the sandy Ultisol. Grazing intensity in both CLI systems was 0.6 AU ha$^{-1.}$

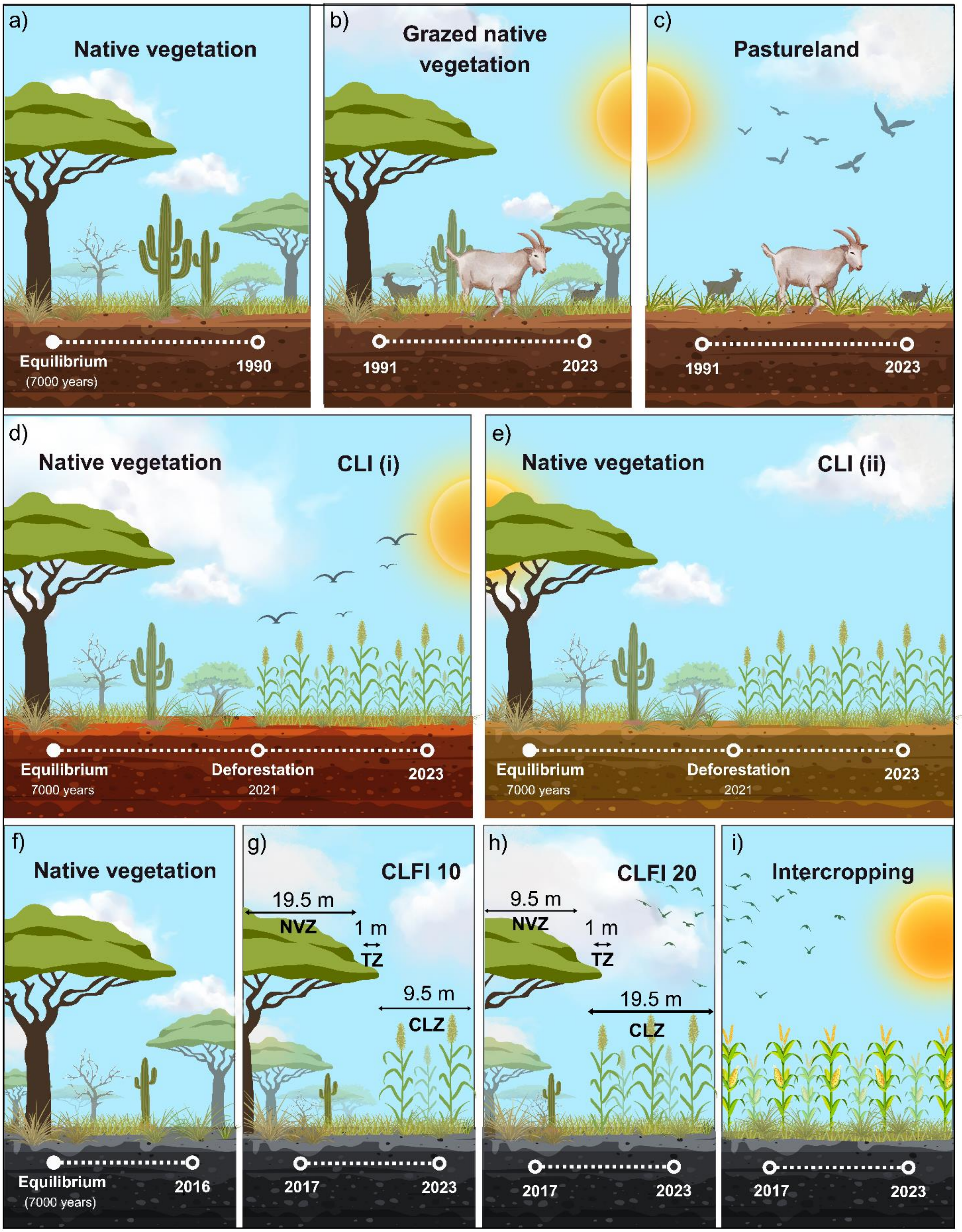


Fig. 2. Schematic representation of the land-use systems evaluated in Petrolina (native vegetation, grazed native vegetation, and pasture), Betânia do Piauí (native vegetation and crop-livestock integration in distinct soil textures), and Sobral (native vegetation, CLFI with 10-m and 20-m cultivation strips, and intercropping). NVZ: native vegetation zone; TZ: transition zone; CLZ: crop-livestock zone.

In Sobral, four systems were studied: native vegetation; two crop-livestock-forestry integration systems established in 2017, differing in their spatial arrangement (CLFI 10 and CLFI 20); and a conventional intercropping system. In CLFI 10, 10-m cultivated strips alternated with 20-m forest strips, whereas CLFI 20 had the opposite arrangement. Sorghum intercropped with massai grass was cultivated for silage during the rainy season in selected years, with soil tillage in those cropping years, and sheep grazed the regrown forage during the dry season. The intercropping system involved maize in the first year and sorghum in the second year combined with forage grasses for silage production

Soil sampling and analysis

Soil sampling was conducted in March 2023 to generate the data required for model calibration and evaluation. A chronosequence approach was adopted at each site, comparing native vegetation and agricultural systems. Sampling followed a grid design with nine points spaced 50 m apart. At diagonal points of the grid, small pits (60 × 60 × 30 cm) were opened, and disturbed samples were collected from 0-10, 10-20, and 20-30 cm. Undisturbed cores from the same layers were obtained with metal rings to determine bulk density (Cerri et al., 2021; Teixeira et al., 2017).

After air drying and sieving (2 mm), visible roots and plant residues were removed manually. Subsamples were then used to determine particle-size distribution, soil pH in CaCl2, and SOC and N concentrations. Texture was measured by the Bouyoucos densimeter method, and bulk density was calculated from oven-dried core mass and ring volume. Carbon and N concentrations were quantified by dry combustion using a TruSpec CN LECO analyzer after additional sieving to 0.150 mm (Gee and Bauder, 2018; Nelson and Sommers, 1996; Teixeira et al., 2017).

Equivalent soil mass corrections were applied using native vegetation as the reference condition at each site, following Ellert and Bettany (1995). Corrected layer thicknesses were then used to calculate SOC and N stocks for the 0-30 cm profile. Ancillary soil properties for all sampled treatments, including texture, pH, and bulk density, are reported in Table S1.

DayCent ecosystem model

The DayCent ecosystem model was used to simulate the dynamics of soil C and nutrients in the evaluated systems. DayCent is the daily time-step version of CENTURY and is widely employed to represent interactions among vegetation, soil, management, and climate, including applications in greenhouse gas inventories and agroecosystem assessments (Del Grosso et al., 2001; Parton et al., 1998; EPA, 2024). The model simulates plant growth, organic matter decomposition, soil temperature and water dynamics, and nutrient cycling, providing a robust framework for evaluating long-term responses of SOC to management and climate.

Model implementation required site-specific daily weather data, soil properties, and management descriptions. The climatic inputs included daily precipitation and minimum and maximum temperature. Soil inputs comprised pH, texture, and bulk density measured in the field, whereas field capacity, wilting point, and saturated hydraulic conductivity were estimated using pedotransfer functions. Management inputs described land-use history, grazing, tillage, crop rotations, and rates and timing of fertilizer application. In the model version used here, simulations were parameterized to represent SOC dynamics in the upper 30 cm of the soil profile (Gurung et al., 2020; Hartman et al., 2022).

Model setup and calibration

Daily weather records from 1985 to 2023 were obtained from INMET stations located near the experimental sites. The equilibrium phase consisted of 7000 years of simulation using the forest submodel to represent native Caatinga vegetation, based on parameterizations from previous studies in the Brazilian semi-arid region. Soil pH, bulk density, and texture measured in the field were incorporated directly, whereas water-related properties were estimated through pedotransfer functions (Althoff et al., 2018; Araújo Neto et al., 2021; Santos et al., 2023; Saxton et al., 1986).

Because SOC dynamics are closely linked to N availability, biological N fixation and atmospheric deposition were also calibrated. Biological fixation for Caatinga vegetation was set at 8.5 kg ha^{-1} yr^{-1}, while atmospheric N deposition was fixed at 5 kg ha^{-1} yr^{-1} based on field studies in Brazilian drylands. Additional adjustments were made to the production potential parameters (PRDX) so that simulated biomass, SOC, and N stocks matched measured values and remained within literature ranges for native Caatinga vegetation.

Land-use conversion histories differed among sites. Native vegetation was removed by cutting in Sobral, Petrolina, and the sandy soil of Betânia do Piauí, whereas slash-and-burn was used in the clayey soil at Betânia do Piauí. Crop, grazing, and fertilization operations were implemented according to the documented history of each treatment. In Betânia do Piauí and Sobral, intercropping systems involving corn and/or sorghum with buffel grass or massai grass were represented using the savanna submodel following the approach proposed by Chiesa et al. (2022), with calibration of crop competition parameters.

For the integrated agricultural systems, DayCent simulations were separated into three zones following Laub et al. (2025): native vegetation zone (NVZ), transition zone (TZ), and crop-livestock zone (CLZ). The final SOC estimates for the integrated systems were calculated as weighted combinations of the simulated zones according to their proportional area in each arrangement. The area fractions of 0.57, 0.06, and 0.37 represented the contribution of the three zones within one hectare.

Alternative management scenarios based on current practices

Beyond the managements observed in the field, additional scenarios were simulated to test plausible intensification pathways. In Petrolina, five grazing-based managements were evaluated: current grazed native vegetation; grazed native vegetation with reduced grazing frequency; current pasture; pasture with reduced grazing; and pasture with reduced grazing plus annual N fertilization at 60 kg ha-1. The first and third scenarios corresponded to the managements currently practiced at the site, whereas the others represented alternative intensification strategies.

In Betânia do Piauí, four CLI configurations were simulated in both clayey and sandy soils. All systems combined sorghum harvested for silage during the rainy season with buffel grass grazed during the dry season, but they differed in soil disturbance and fertilization regime: conventional tillage with low fertilization every five years, conventional tillage with annual fertilization, no-tillage with low fertilization every five years, and no-tillage with annual fertilization. These scenarios allowed assessment of how soil texture interacts with management intensity to control SOC trajectories.

In Sobral, six scenarios were considered. Two corresponded to CLFI 10 under conventional tillage and no-tillage, two to CLFI 20 under conventional tillage and no-tillage, and two to intercropping under conventional tillage and no-tillage. CLFI management involved years of silage production followed by years dominated by grazing, whereas the intercropping system was harvested annually. The tillage and fertilization histories reflected the local production systems. The simulated intensification strategies, namely reduced grazing pressure, mineral fertilization, and no-tillage, were selected because previous evidence in drylands indicates their potential to improve residue return, root production, nutrient cycling, and soil carbon retention relative to more extensive or disturbance-intensive systems.

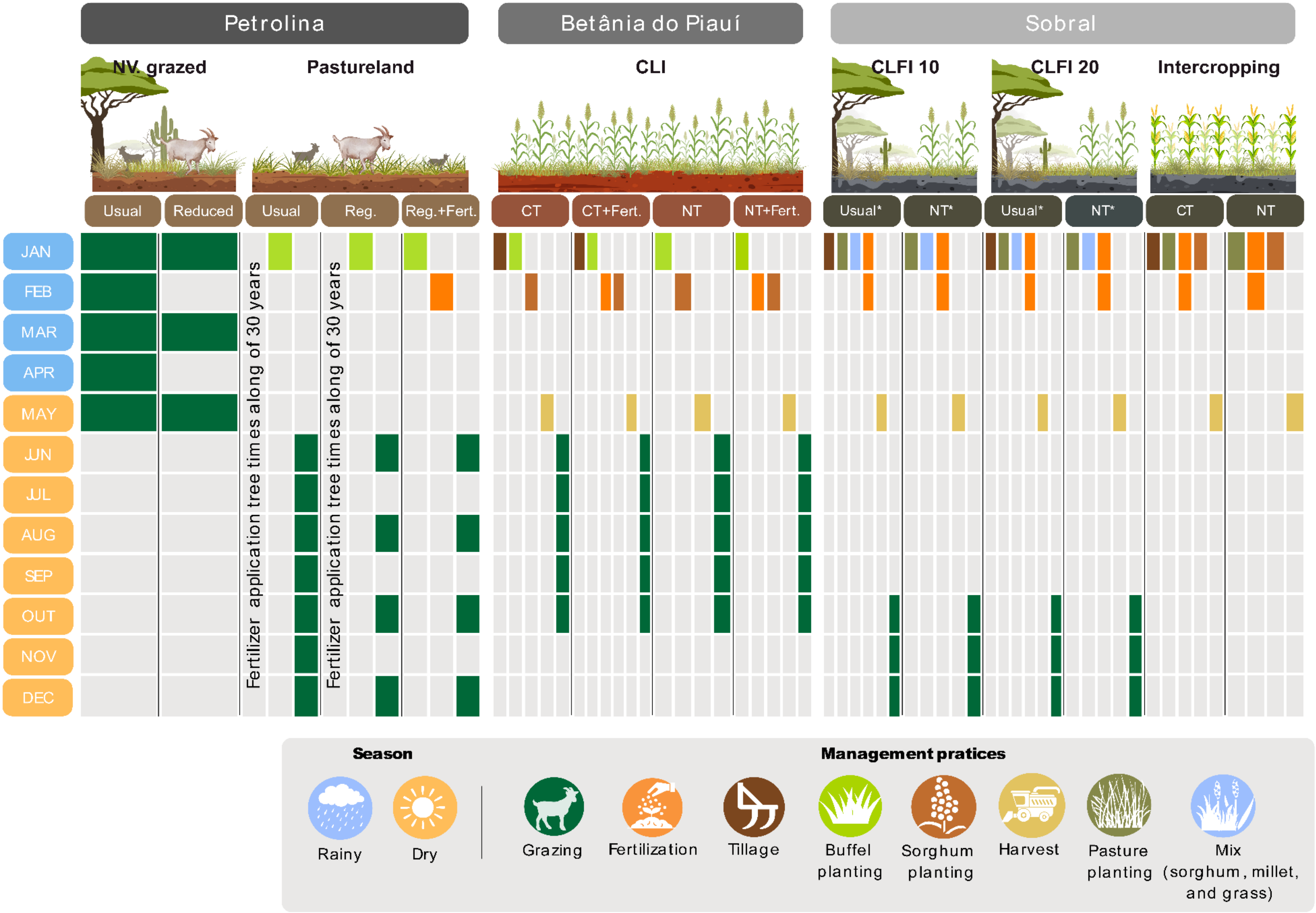


Fig. 3. Chronology of current and intensified management scenarios simulated for the three study sites. NV: native vegetation; Reg: reduced grazing; Fert: fertilization; CLI: crop-livestock integration; CT: conventional tillage; NT: no-tillage; CLFI: crop-livestock-forest integration.

Future climate scenarios

Future simulations were carried out to quantify the effect of projected climate change on SOC dynamics under the current and intensified management systems. Three climate conditions were considered: the current climate represented by the historical weather series from 1985 to 2023, and two future Shared Socioeconomic Pathways, SSP2-4.5 and SSP5-8.5. These scenarios represent, respectively, an intermediate and a high-emissions trajectory, with stronger warming and drying expected under SSP5-8.5 (IPCC, 2021). Projected climate data were obtained from the NASA Earth Exchange Global Daily Downscaled Projections based on CMIP6 (NEX-GDDP-CMIP6). Five general circulation models were used: ACCESS-CM2, CanESM5, GFDL-ESM4, MRI-ESM2-0, and NorESM2-LM. Simulations covered the 2024-2100 period, and each treatment was run separately for each climate model. Results were subsequently averaged across models. CO2 trajectories associated with each SSP were also incorporated to account for their potential influence on crop productivity (Meinshausen et al., 2020; Thrasher et al., 2022).

Statistical analysis

Model performance was assessed by comparing simulated and measured values of crop yield, SOC, and soil N stocks using the statistical indicators recommended by Smith et al. (1997). These metrics included the correlation coefficient (r), root mean square error (RMSE), relative RMSE (RRMSE), coefficient of determination (R^2 or CD), model efficiency (EF), and bias. RMSE and RRMSE quantified the magnitude of prediction errors, R^2 assessed the variance explained by the simulations, EF compared model performance against the observed mean, and bias indicated systematic overestimation or underestimation. All calculations were performed with the MODEVAL tool (Nikulin et al., 2011; Richter et al., 2012).

Results

Model performance

Measured and simulated SOC and N stocks in the 0-30 cm layer differed among sites and land-use systems, but overall agreement between observations and simulations was satisfactory (Table 1; Fig. 4). In Petrolina, SOC tended to be slightly underestimated, whereas N was generally overestimated. In the clayey soil of Betânia do Piauí, the largest discrepancy in SOC occurred in native vegetation, while in the sandy soil the differences between measured and simulated stocks were smaller for both SOC and N. In Sobral, the largest underestimations of SOC were observed in CLFI 20 and intercropping. For most treatments, however, simulated values remained within the 95% confidence interval or standard deviation of the measured data.

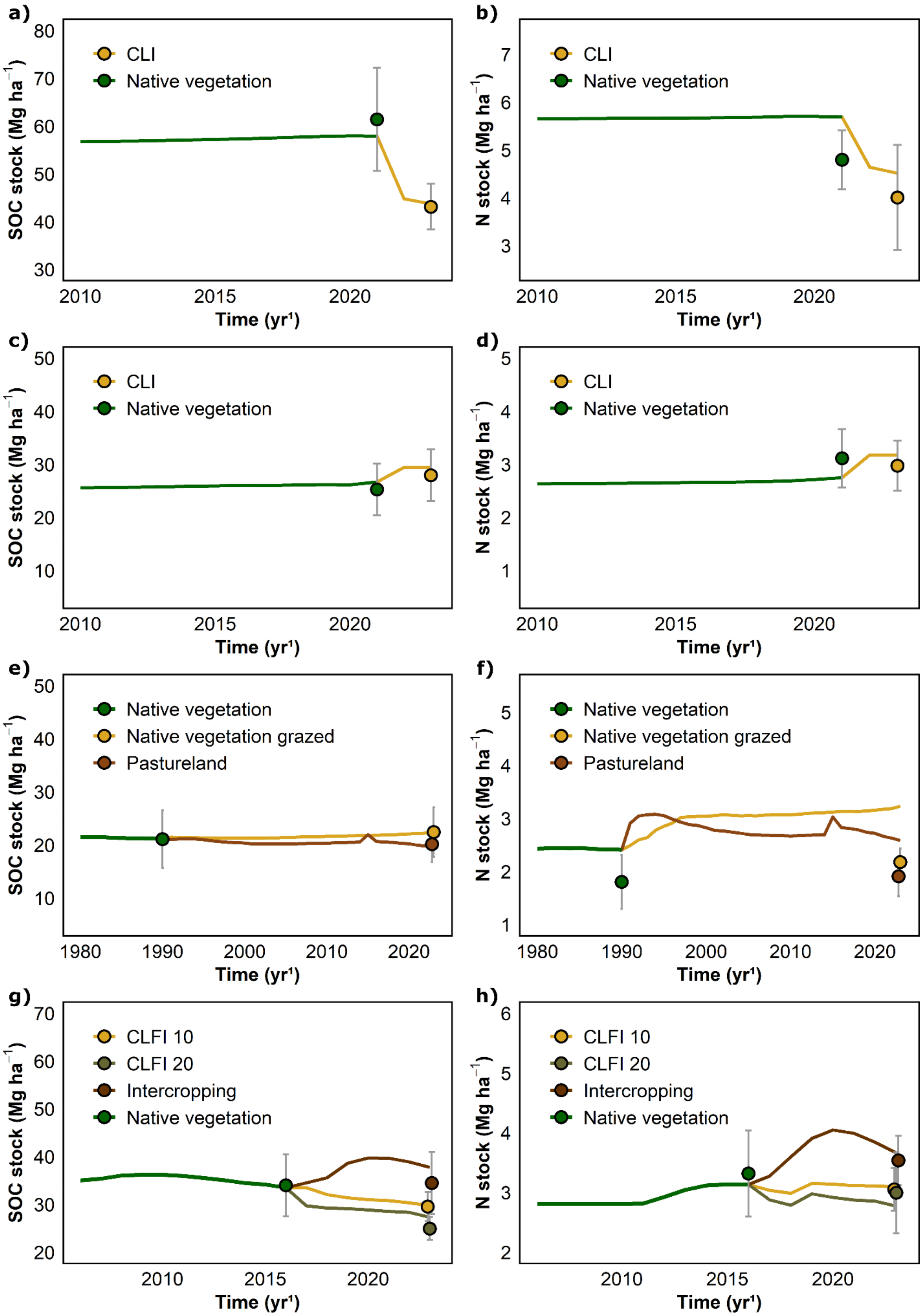
Temporal trajectories reconstructed by the simulations indicated contrasting responses after land-use conversion. In the clayey soil of Betânia do Piauí, establishment of CLI reduced both SOC and N relative to native vegetation, whereas in the sandy soil the CLI system showed rapid increases in simulated SOC and N. In Petrolina, both pasture and grazed native vegetation tended to increase SOC and N over time. In Sobral, simulated values for CLFI 10, CLFI 20, and intercropping were consistent with the observed variability in measured stocks.

Site-specific statistics reinforced this overall pattern (Table 2). Betânia do Piauí showed high model efficiency for SOC, Petrolina presented a more moderate fit, and Sobral displayed intermediate to high predictive performance. Simulated crop biomass values were also coherent with measured or literature values for buffel grass, sorghum, maize, and massai grass (Table S3).

Table 1. Measured and simulated soil organic carbon (C) and nitrogen (N) stock values (0–30 cm depth) of native vegetation and agricultural systems and their difference at three study sites (Petrolina, Betânia do Piauí, and Sobral) located in the Brazilian drylands region, Brazil.

Location	**Systems**	**Soil organic C stock (Mg C ha^{-1})**			**Soil N stock (Mg N ha^{-1})**		
		Measured	**Simulated**	**Difference**	**Measured**	**Simulated**	**Difference**
Petrolina (PE)	Native Vegetation	21.091 ± 5.42	21	0.09	1.805 ± 0.51	2.82	-1.02
	Grazed native vegetation	24.421 ± 4.65	22.49	1.93	2.178 ± 0.26	3.25	-1.07
	Pastureland	20.136 ± 3.36	19.62	0.52	1.908 ± 0.38	2.51	-0.6
Betânia do Piauí (PI)	Native Vegetation (CS)	61.403 ± 10.80	56.59	4.81	4.793 ± 0.62	5.7	-0.91
	CLI (CS)	43.103 ± 4.79	45.86	-2.76	4.005 ± 1.10	4.51	-0.51
	Native Vegetation (SS)	25.268 ± 4.87	25.76	-0.5	3.114 ± 0.55	2.69	-0.42
	CLI (SS)	27.943 ± 4.88	29.4	-1.45	2.979 ± 0.47	3	-0.02
Sobral (CE)	Native Vegetation	33.995 ± 6.49	33.51	0.49	3.317 ± 0.72	2.93	0.39
	CLFI 10	29.554 ± 3.03	29.78	-0.23	3.051 ± 0.36	3.03	0.02
	CLFI 20	24.942 ± 2.40	26.93	-1.99	2.994 ± 0.68	2.77	-0.22
	Intercropping	34.457 ± 6.52	37.06	-2.94	3.535 ± 0.41	3.66	-0.13

* Values after the symbol represent the standard deviation of the mean (n = 9). Integrated livestock-crop-forest. CS: Clayey soil. SS: Sandy soil.


a)
80
70
60
50
40
30
SOC stock (Mg ha^{-1})
CLI
Native vegetation
2010
2015
2020
Time (yr¹)
b)
7
6
5
4
3
N stock (Mg ha^{-1})
CLI
Native vegetation
2010
2015
2020
Time (yr¹)
c)
50
40
30
20
10
SOC stock (Mg ha^{-1})
CLI
Native vegetation
2010
2015
2020
Time (yr¹)
d)
5
4
3
2
1
N stock (Mg ha^{-1})
CLI
Native vegetation
2010
2015
2020
Time (yr¹)
e)
50
40
30
20
10
SOC stock (Mg ha^{-1})
Native vegetation
Native vegetation grazed
Pastureland
1980
1990
2000
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Time (yr¹)
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5
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N stock (Mg ha^{-1})
Native vegetation
Native vegetation grazed
Pastureland
1980
1990
2000
2010
2020
Time (yr¹)
g)
70
60
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30
20
SOC stock (Mg ha^{-1})
CLFI 10
CLFI 20
Intercropping
Native vegetation
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N stock (Mg ha^{-1})
CLFI 10
CLFI 20
Intercropping
Native vegetation
2010
2015
2020
Time (yr¹)

Fig. 4. Measured and simulated SOC and N stocks in the 0-30 cm layer for the evaluated systems in Betânia do Piauí, Petrolina, and Sobral. Bars indicate the standard deviation of the measured means.

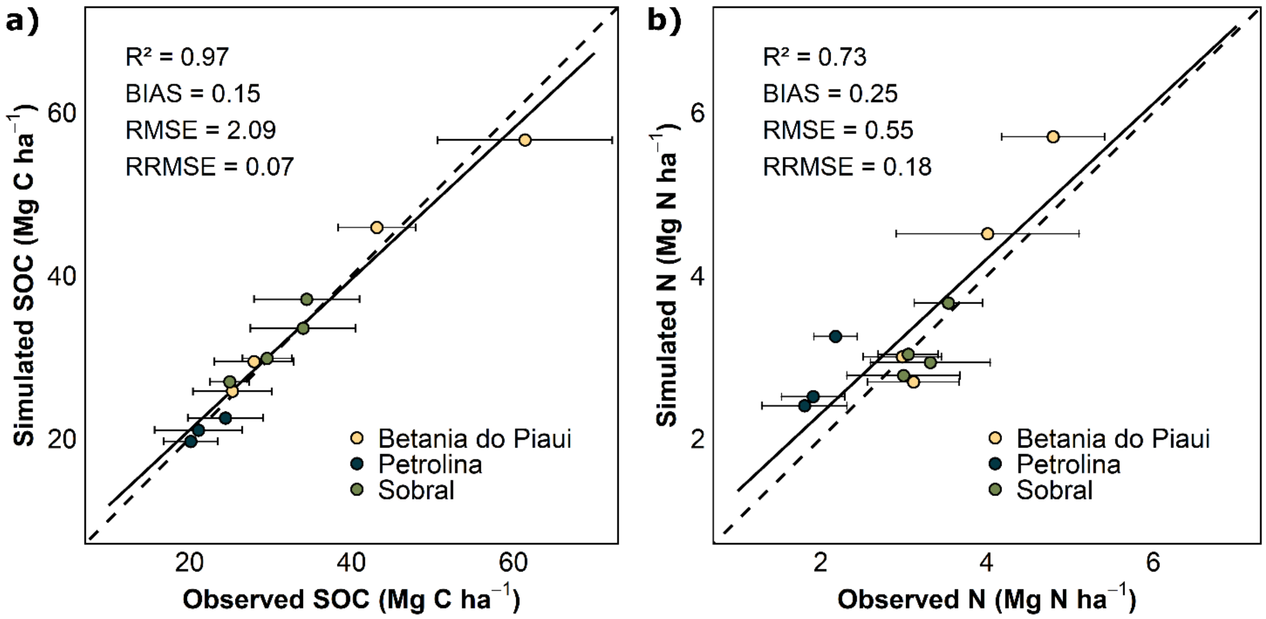

Fig. 5. Relationship between measured and simulated SOC and N stocks across the evaluated agroecosystems.

Across all sites and systems, simulated SOC was strongly related to observed SOC (R² = 0.97, RMSE = 2.09 Mg C ha^{-1}, bias = 0.15, RRMSE = 0.07). Soil N simulations also performed reasonably well, although with lower accuracy than SOC (R² = 0.73, RMSE = 0.55 Mg N ha^{-1}, bias = 0.25, RRMSE = 0.18).

Table 2. Statistical indicators used to evaluate model performance for SOC, N, and crop biomass across the three study sites.

Experimental site	**Variable**	**Statistical test**			
		r	**RMSE**	**CD**	**EF**
Petrolina - PE	Soil organic C	0.96	3.43	0.61	0.56
	Soil N	0.97	42.47	0.02	-0.4
Betânia do Piauí - PI	Soil organic C	0.98	5.68	0.96	0.94
	Soil N	0.96	11.31	0.41	0.29
Sobral - CE	Soil organic C	0.97	6.39	0.81	0.76
	Soil N	0.84	23.23	0.41	0.62
	Intercropping (Maize + Marandu grass)	0.92	3.21	0.8	-1.2

	ILPF (Sorghum + Marandu grass)	0.92	3.21	0.8	-1.2
Best fit	-	1	0	1	-

r: correlation coefficient; RMSE: root mean square error; CD: coefficient of determination; EF: model efficiency.

Effect of system intensification on SOC stocks

Management intensification generally increased SOC stocks in Betânia do Piauí and Petrolina, although the magnitude of the response depended on soil texture and the specific strategy adopted (Fig. 6a, d, and g). In Betânia do Piauí, the highest SOC values were consistently associated with no-tillage and annual fertilization, especially in the clayey soil, whereas conventional tillage systems were more vulnerable to SOC declines during drier periods. In Petrolina, reduced grazing and fertilization also promoted higher SOC values in both native vegetation and pasture-based systems. In Sobral, no-tillage improved SOC retention in all agricultural systems relative to conventional tillage, but it did not fully reverse the long-term tendency toward SOC depletion.

Predicted SOC stocks under future climate change scenarios

Under both SSP scenarios, SOC stocks declined relative to the current climate at all three sites (Fig. 6; Figs. S2-S4). In Betânia do Piauí, sandy soils accumulated less SOC than clayey soils under every management system. No-tillage with annual fertilization produced the highest SOC stocks under the current climate, while conventional tillage with low fertilization showed the poorest performance. Even the best-performing systems, however, lost SOC under future climate forcing, with stronger reductions under SSP5-8.5. In Petrolina, reduced grazing and fertilization increased SOC relative to the more extensive systems under the current climate. Nonetheless, future warming and drying narrowed the differences among managements and drove convergence toward lower SOC levels by 2100, particularly under SSP5-8.5. Pasture systems were especially sensitive to the climate signal.

In Sobral, all agricultural systems showed progressive SOC decline under both present and projected climates. No-tillage consistently lessened these losses, particularly in intercropping, but could not fully prevent them. Overall, the simulations indicate that intensification strategies improved SOC retention but were insufficient to completely offset the negative effects of projected climate change. Complementary results for net primary productivity and heterotrophic respiration are presented in Figs. S5-S7.

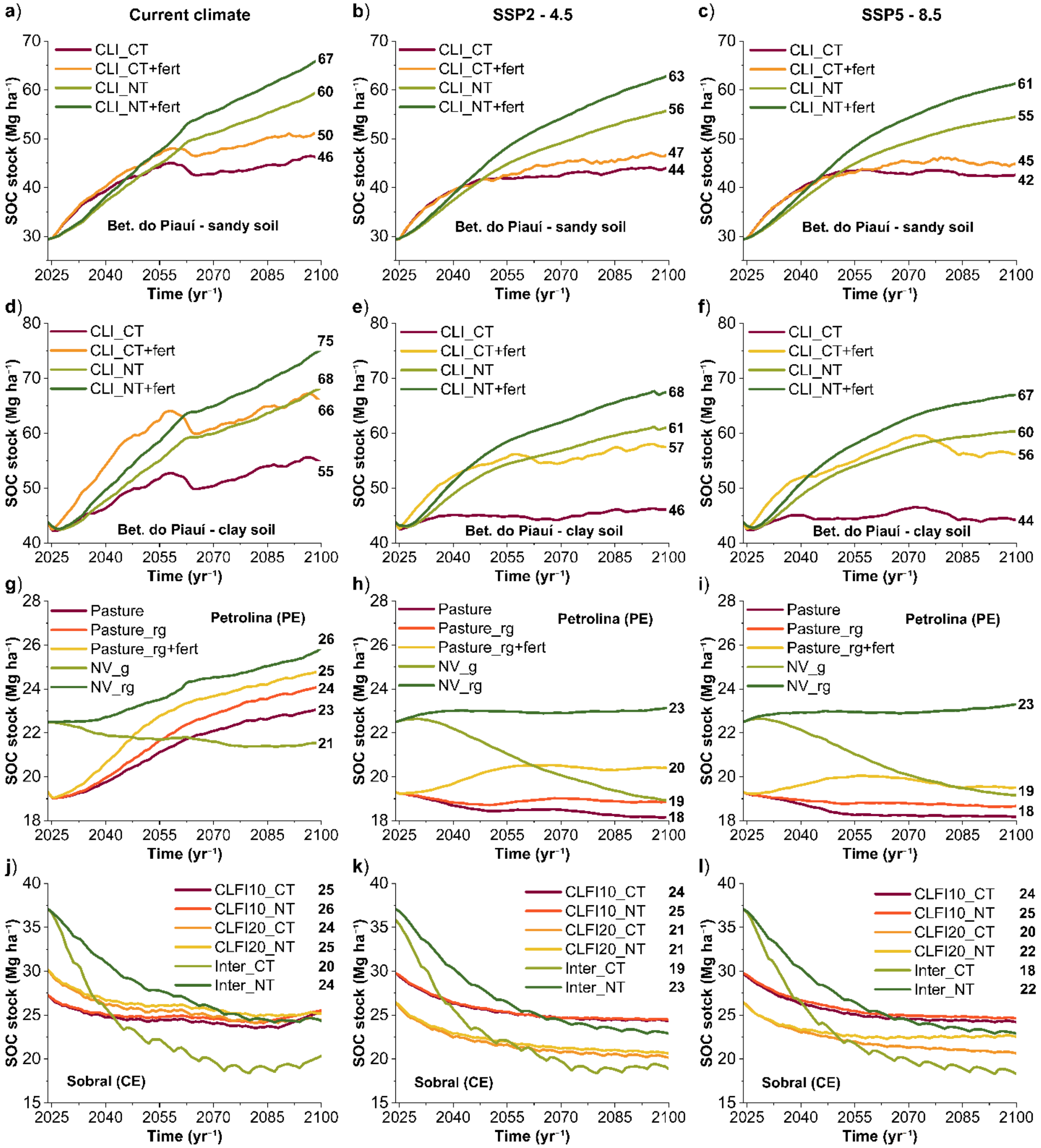

Fig. 6. Simulated SOC stocks from 2024 to 2100 under the current climate, SSP2-4.5, and SSP5-8.5 for the management systems evaluated in Betânia do Piauí, Petrolina, and Sobral.

Conclusion

This study showed that SOC dynamics in Brazilian drylands are strongly controlled by both land management and climate. Conversion of native vegetation to agricultural systems generally reduced SOC, especially when associated with burning, low-input management, or conventional tillage. In contrast, annual fertilization, no-tillage, and better grazing management increased SOC retention and reduced losses, particularly in integrated systems. Despite these benefits, all sites experienced SOC declines under SSP2-4.5 and SSP5-8.5, with the most pronounced vulnerability observed in sandy soils. Therefore, sustainable intensification can improve resilience and partly buffer future losses, but it cannot fully eliminate the adverse effects of a warmer and drier climate. Long-term adaptation in Brazilian drylands will depend on combining conservation practices, improved nutrient management, integrated production systems, and broader climate adaptation strategies.

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Appendix

Table S1. Soil chemical and physical attributes (0–30 cm depth) of sampled treatments in Petrolina (PE), Betânia do Piauí (PI), and Sobral (CE) located in the Brazilian Drylands region.

Experimental site	Treatments	Layer	Clay	Silt	Sand	pH	BD
		cm		---------- g.kg^{1} ----------		CaCl$_2$	-- g.cm
Petrolina (PE)	Native vegetation	0-10	74.9	51.5	873.6	4.5	1.52
		10-20	99.9	77.2	822.9	4.2	1.60
		20-30	200.2	64.8	735.0	4.1	1.61
	Grazed native vegetation	0-10	99.5	118.2	782.3	4.7	1.56
		10-20	149.9	135.5	714.6	4.4	1.59
		20-30	275.3	122.3	602.4	4.5	1.60
	Pastureland	0-10	100.0	86.2	813.8	4.1	1.60
		10-20	150.8	100.6	748.6	3.9	1.61
		20-30	199.5	152.1	648.4	3.8	1.62
Betânia do Piauí (PI)	Native vegetation (CS)	0-10	348.3	124.0	527.7	6.3	1.24
		10-20	373.0	134.1	492.9	5.8	1.26
		20-30	452.5	100.0	447.5	5.3	1.26
	CLI (CS)	0-10	350.2	109.5	540.3	5.6	1.20
		10-20	420.4	93.7	485.9	5.3	1.31
		20-30	467.1	89.4	443.5	5.1	1.30
	Native vegetation (SS)	0-10	124.3	45.0	830.7	5.6	1.61
		10-20	124.8	71.7	803.5	5.4	1.64
		20-30	198.7	73.8	727.5	5.1	1.63
	CLI (SS)	0-10	74.3	53.0	872.7	5.1	1.56
		10-20	74.8	54.4	870.8	4.9	1.59
		20-30	100.1	22.2	877.7	4.7	1.57
Sobral (CE)	Native vegetation	0-10	124.9	127.6	747.5	4.6	1.47
		10-20	125.0	129.7	745.3	4.6	1.63
		20-30	174.4	193.4	632.2	4.6	1.65
	CLFI 10	0-10	99.6	131.1	769.3	4.9	1.43
		10-20	148.7	149.4	701.9	4.8	1.58
		20-30	272.7	125.2	602.1	4.8	1.63
	CLFI 20	0-10	124.6	188.7	686.7	4.7	1.43
		10-20	99.6	147.0	753.4	4.7	1.61
		20-30	197.8	128.1	674.1	4.8	1.67
	Intercropping	0-10	149.3	162.7	688.0	5.3	1.50
		10-20	172.8	141.9	685.3	5.3	1.65
		20-30	224.9	133.5	641.6	5.5	1.68

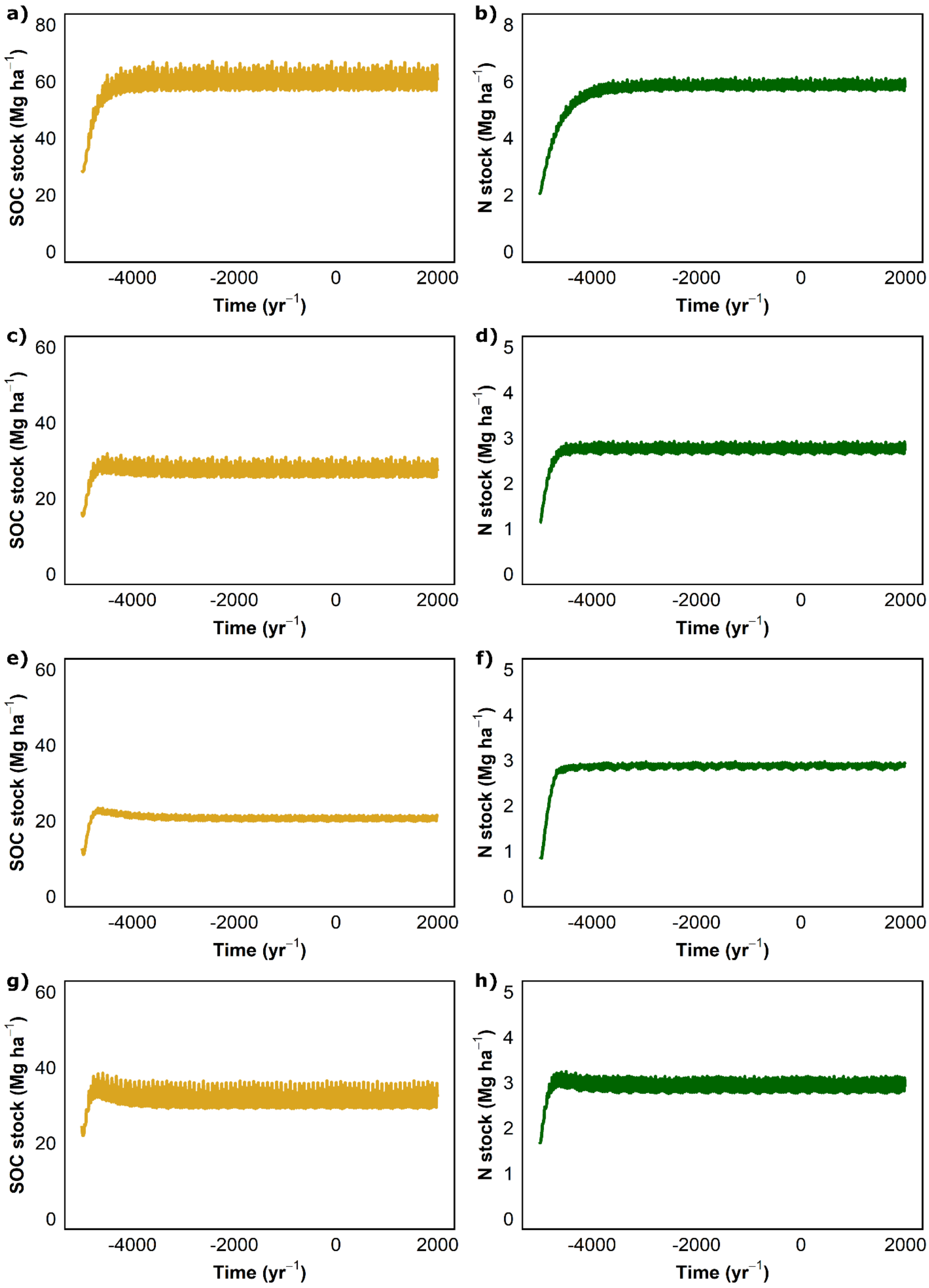
a)
b)
c)
d)
e)
f)
g)
h)
SOC stock (Mg ha^{-1})
N stock (Mg ha^{-1})
Time (yr^{-1})
0
20
40
60
80
0
2
4
6
8
1
3
5
-4000
-2000
0
2000

Fig. S1. Equilibrium of the soil organic carbon (SOC; Mg C ha^{-1}) and soil nitrogen (N; Mg N ha^{-1}) stocks (0–30 cm depth) under the assessed treatments in ***a)*** and ***b)*** is Betânia do Piauí – PI (Clay soil); ***c)*** and ***d)*** is Betânia do Piauí – PI (Sandy soil); ***e)*** and ***f)*** is Petrolina – PE, ***g)*** and ***h)*** Sobral – CE, located in the Brazilian drylands along of 7000 years.

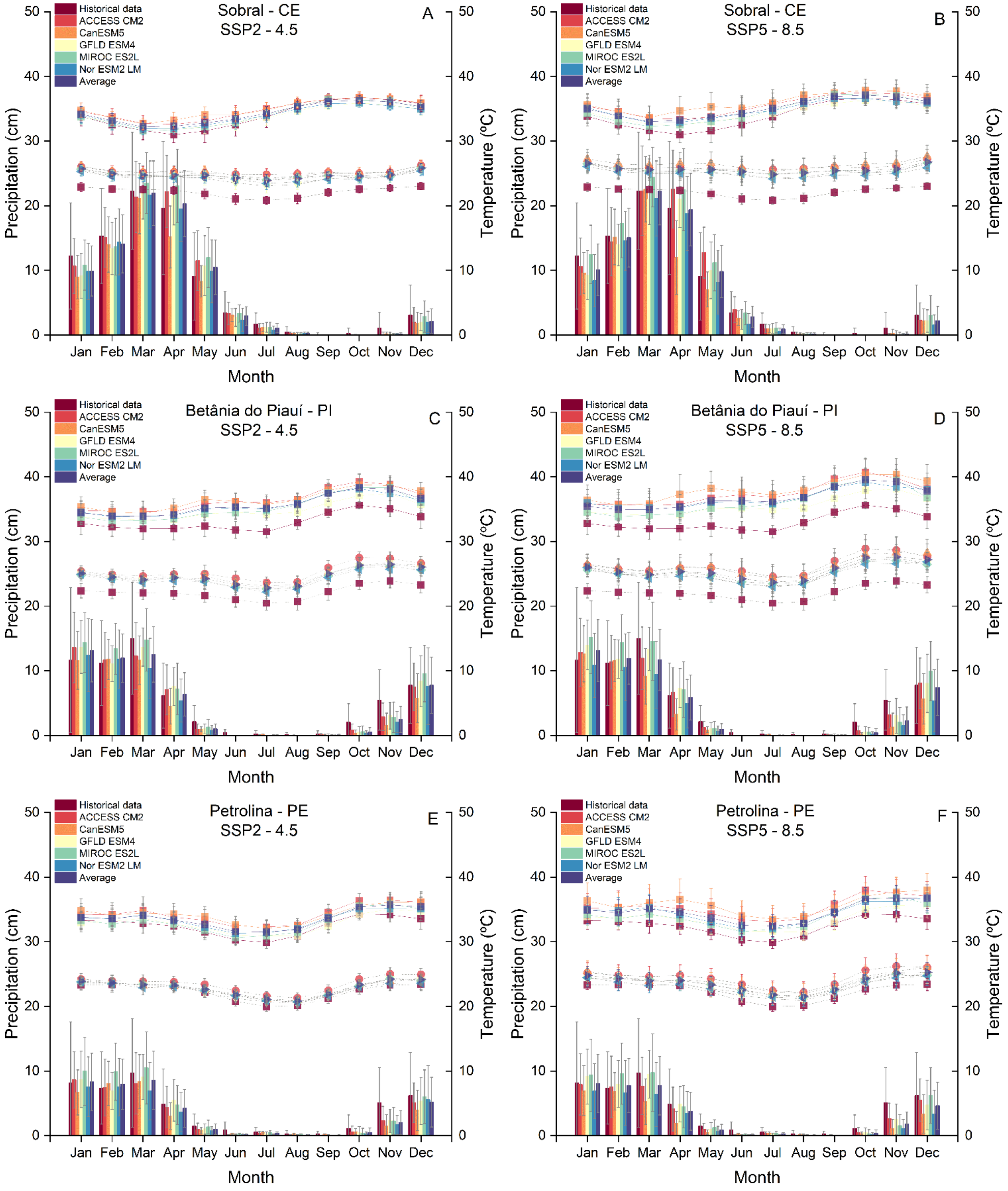

Figure S2. Historical and projected monthly precipitation (bars) and maximum (solid line) and minimum (dashed line) temperature for Sobral (A – B), Betânia do Piauí (C – D), and Petrolina (E – F) scenarios (SSP2 – 4.5 and SSP5 – 8.5) simulated by the ACCESS-CM2, CanESM5, GFDL ESM4, MIROC ESL2, and Nor ESM2 LM models for the period between 2023-2070.

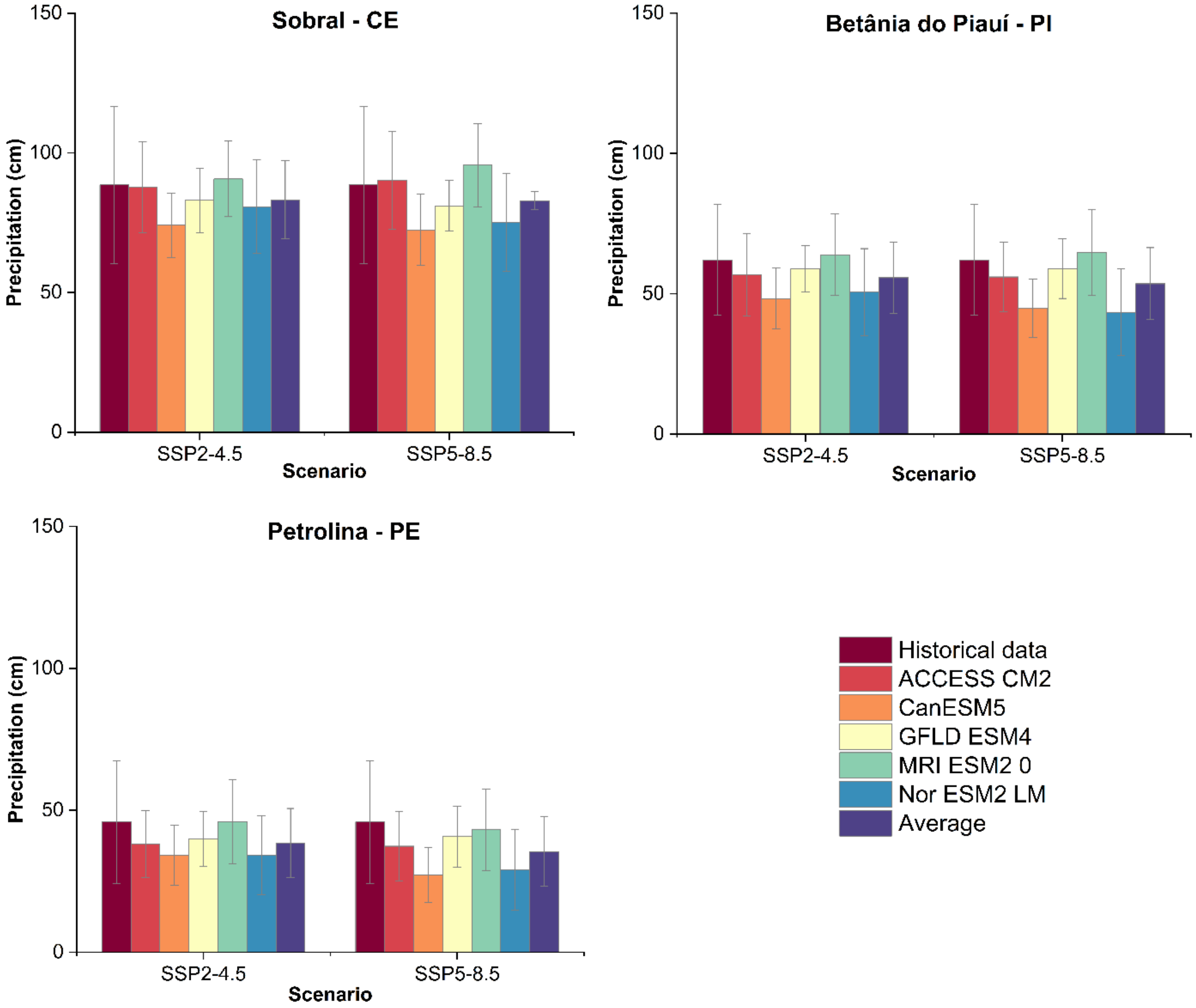

Figure S3. Historical measured and simulated (ACCESS-CM2, CanESM5, GFDL ESM4, MIROC ESL2, Nor ESM2 LM*)* annual precipitation obtained for Sobral – CE, Betânia do Piauí – PI, and Petrolina - PE. Vertical bars represent the standard deviation of the average.

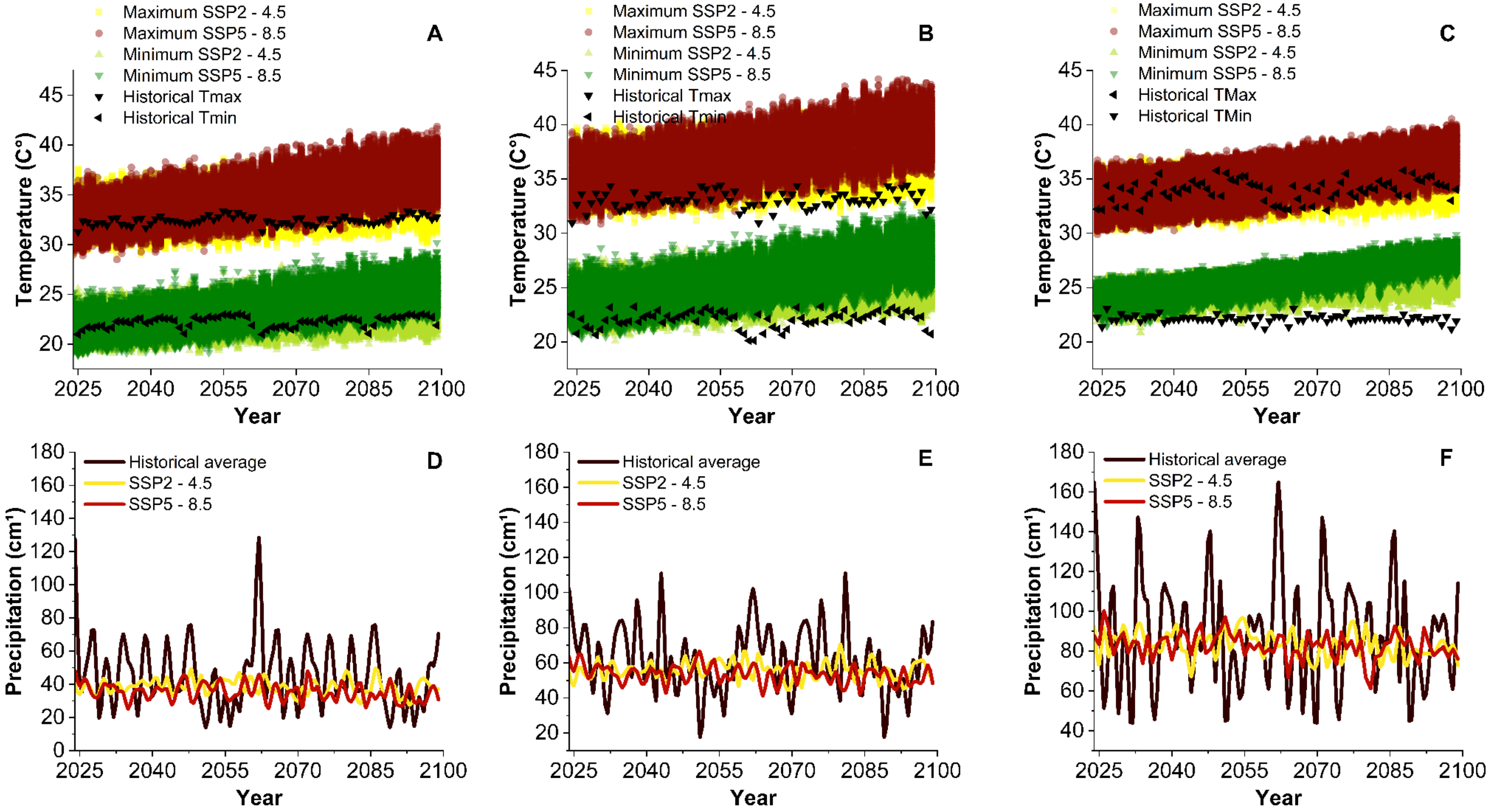

Figure S4. Projected maximum and minimum temperature and precipitation for the Petrolina (A and D), Betânia do Piauí (B and E), and Sobral (C and F), under SSP2 – 4.5 and SSP5 – 8.5 climate scenarios obtained from the ACCESS-CM2, CanESM5, GFDL-ESM4, MRI-ESM2-0, and NorESM2-LM models. Historical climate data (1985-2023) have been superimposed on these graphs as black dots and lines to highlight the differences between the current climate and climate change projection

Table S2. Crop, tree, and others parameters adjusted in the DayCent model.

Parameter	**Description**	**Default**	**Present study value**			**Reference**
			Petrolina - PE	*Betânia do Piauí - PI*	*Sobral - CE*	
Tree.100	Native vegetation (Caatinga)					
PRDX (2)	Maximum gross forest production (g biomass m^2 month^1).	0.5	0.53	0.95	1.50	
DECW1	Decomposition rate for wood1 (dead fine branch) per year.	1.5	4.5	4.5	4.5	Althoff et al. (2018); Araújo Neto et al. (2021)
DECW2	Decomposition rate for wood2 (dead large wood) per year.	0.5	3.8	3.8	3.8	Althoff et al. (2018); Araújo Neto et al. (2021)
DECW3	Decomposition rate for wood3 (dead coarse root) per year.	0.6	4.0	4.0	4.0	Althoff et al. (2018); Araújo Neto et al. (2021)
MAXLAI	Theoretical maximum leaf area index achieved in a mature forest.	20	1.9	1.9	1.9	Althoff et al. (2018); Araújo Neto et al. (2021)
KLAI	Large wood mass (g C m^2) at which half of theoretical maximum leaf area (maxlai) is achieved.	2000	39.6	39.6	39.6	Althoff et al. (2018); Araújo Neto et al. (2021)

Parameter	**Description**	**Default**	**Present study value**			**Reference**
			Petrolina - PE	*Betânia do Piauí - PI*	*Sobral - CE*	
Crop.100	Pasture (Buffel grass)					
PRDX (2)	Coefficient for calculating potential aboveground monthly production as a	0.1 - 5	0.62	1.20	1.30	

	function of solar radiation outside the atmosphere for pasture.					
PPDF (1)	Optimum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth.	30	28	28	28	Santos et al. (2010).
SNFXMX (1)	Symbiotic N fixation maximum for grass/crop.	0.015	0	0	0	Carvalho et al. (2017).

Parameter	**Description**	**Default**	**Present study value**
			---All sites---
Trem.100	Parameters used to represent the grazing in the native vegetation.		
EVNTYP	Type of event (0 = grazing).	---	0.00
REMF (1)	Fraction of live leaves removed.	---	0.1
REMF (2)	Fraction of fine branches removed.	---	0.00
REMF (3)	Fraction of large wood removed.	---	0.00
REMF (4)	Fraction of fine roots removed.	---	0.00
REMF (5)	Fraction of coarse roots removed.	---	0.00
FD (1)	Fraction of fine roots killed.	---	0.00
FD (2)	Fraction of coarse roots killed.	---	0.00
RETF (1,1)	Fraction of C from removed live leaves returned to system.	---	0.3

RETF (1,2)	Fraction of N from removed live leaves returned to system.	---	0.65	
RETF (1,3)	Fraction of P from removed live leaves returned to system.	---	0.95	
RETF (1,4)	Fraction of S from removed live leaves returned to system.	---	0.725	
RETF (2,1)	Fraction of C from removed fine branches returned to system.	---	0.00	
RETF (2,2)	Fraction of N from removed fine branches returned to system.	---	0.00	
RETF (2,3)	Fraction of P from removed fine branches returned to system.	---	0.00	
RETF (2,4)	Fraction of S from removed fine branches returned to system.	---	0.00	
RETF (3,1)	Fraction of C from removed large wood returned to system.	---	0.00	
RETF (3,2)	Fraction of N from removed large wood returned to system.	---	0.00	
RETF (3,3)	Fraction of P from removed large wood returned to system.	---	0.00	
RETF (3,4)	Fraction of S from removed large wood returned to system.	---	0.00	
SNFXMX (1)	Symbiotic N fixation maximum for grass/crop.	---	0.00	

	Description	Default	Present study value	Reference

Parameter			*Petrolina - PE*	*Betânia do Piauí - PI*	*Sobral - CE*	
Sorghum - Intercropping (converted into TREE.100 file).						
PRDX (2)	Potential production as a function of solar radiation outside the atmosphere.	0 - 5		1.70	1.20	
KLAI	Large wood mass (g C/m^2) at which half of theoretical maximum leaf area (MAXLAI) is achieved.	---	---	50.0	50.0	Della Chiesa et al. (2022).
LAITOP	Parameter determining the relationship between LAI and forest production.	---	---	-0.47	-0.47	Della Chiesa et al. (2022).
MAXLAI	Theoretical maximum leaf area index (LAI) achieved in a mature forest.	---	---	5	5	
BASFC2	Relates tree basal area to grass N fraction; higher values (0 to 1) give more N to trees; if not running a savanna set to 1.	---	---	1.9	1.5	
SITPOT	The SITPOT variable is dynamic and computed as a function of average annual precipitation (site.100). The value in the tree.100 will be used as a multiplier; recommended value for tree.100 is 1.0.	---	---	0.1	0.5	

Parameter	**Description**	**Default**	**Present study value**			**Reference**
			Petrolina - PE	*Betânia do Piauí - PI*	*Sobral - CE*	

Maize - Intercropping (converted into TREE.100 file).

PRDX (2)	Potential production as a function of solar radiation outside the atmosphere.	0 - 5	---	---	1.50	
KLAI	Large wood mass (g C/m^2) at which half of theoretical maximum leaf area (MAXLAI) is achieved.	---	---	---	50	Della Chiesa et al. (2022).
LAITOP	Parameter determining the relationship between LAI and forest production.	---	---	---	-0.45	Locatelli et al. (2025)
MAXLAI	Theoretical maximum leaf area index (LAI) achieved in a mature forest.	---	---	---	5	Locatelli et al. (2025)
BASFC2	Relates tree basal area to grass N fraction; higher values (0 to 1) give more N to trees; if not running a savanna set to 1.	---	---	---	1.5	
SITPOT	The SITPOT variable is dynamic and computed as a function of average annual precipitation (site.100). The value in the tree.100 will be used as a multiplier; recommended value for tree.100 is 1.0.	---	---	---	0.5	

Parameter	**Description**	**Default**	**Present study value**		
			Petrolina - PE	*Betânia do Piauí - PI*	*Sobral - CE*
TREM.100 (For harvesting Sorghum/Maize turned into TREE.100)					
EVNTYP	Event type flag (0 = non-fire, 1 = fire)	0 - 1	-	0	0

REMF (1)	Fraction of live leaves removed from pool	0 - 1	-	1	1
REMF (2)	Fraction of live fine branches removed from pool	0 - 1	-	1	1
REMF (3)	Fraction of live large wood removed from pool	0 - 1	-	1	1
FD (1)	Fraction of live fine roots that die	0 - 1	-	1	1
FD (2)	Fraction of live coarse roots that die	0 - 1	-	1	1
RETF (1,1)	Fraction of C in killed live leaves that is returned to the system	0 - 1	-	0.4	0.4
RETF (1,2)	Fraction of N in killed live leaves that is returned to the system	0 - 1	-	0.25	0.25
RETF (1,3)	Fraction of P in killed live leaves that is returned to the system	0 - 1	-	0.4	0.4
RETF (1,4)	Fraction of S in killed live leaves that is returned to the system	0 - 1	-	0.4	0.4
RETF (2,1)	Fraction of C in killed fine branches that is returned to the system	0 - 1	-	0.4	0.4
RETF (2,2)	Fraction of N in killed fine branches that is returned to the system	0 - 1	-	0.25	0.25
RETF (2,3)	Fraction of P in killed fine branches that is returned to the system	0 - 1	-	0.4	0.4
RETF (2,4)	Fraction of S in killed fine branches that is returned to the system	0 - 1	-	0.4	0.4

Parameter	**Description**	**Default**	**Present study value**		
			Petrolina - PE	*Betânia do Piauí - PI*	*Sobral - CE*
Crop.100	Mix (mix of plants between sorghum, millet and massai grass).				
PRDX (1)	Radiation use efficiency (g C/MJ PAR)	---	---	---	2
PPDF (1)	Photoperiod function parameter 1	---	---	---	30

PPDF (2)	Photoperiod function parameter 2	---	---	---	45
PPDF (3)	Photoperiod function parameter 3	---	---	---	1
PPDF (4)	Photoperiod function parameter 4	---	---	---	2.5
BIOFLG	Biomass harvest flag (0 = no biomass removal, 1 = biomass removed)	---	---	---	0
BIOK5	Maximum daily biomass production (kg/ha)	---	---	---	1220
PLTMRF	Plant mortality rate factor	---	---	---	0.67
FULCAN	Leaf area index at full canopy	---	---	---	133.3
FRTCINDX	Index determining root carbon allocation pattern	---	---	---	2
FRTC (1)	Fraction of root C allocated at emergence	---	---	---	0.23
FRTC (2)	Fraction of root C at full canopy	---	---	---	0.05
FRTC (3)	Day of year to start transition to full canopy allocation	---	---	---	90
FRTC (4)	Fraction of root C at end of growing season	---	---	---	0.15
FRTC (5)	Minimum root C fraction	---	---	---	0.1
CFRTCN (1)	Root C:N ratio at emergence	---	---	---	0.4
CFRTCN (2)	Root C:N ratio at full canopy	---	---	---	0.25
CFRTCW (1)	Aboveground biomass C:N ratio at emergence	---	---	---	0.43
CFRTCW (2)	Aboveground biomass C:N ratio at full canopy	---	---	---	0.17
BIOMAX	Maximum standing live biomass (gC/m²)	---	---	---	400
PRAMN (1,1)	Minimum allocation to organ 1, age class 1	---	---	---	23.3
PRAMN (2,1)	Minimum allocation to organ 2, age class 1	---	---	---	230
PRAMN (3,1)	Minimum allocation to organ 3, age class 1	---	---	---	240

PRAMN (1,2)	Minimum allocation to organ 1, age class 2	---	---	---	58.3
PRAMN (2,2)	Minimum allocation to organ 2, age class 2	---	---	---	230
PRAMN (3,2)	Minimum allocation to organ 3, age class 2	---	---	---	213.3
PRAMX (1,1)	Maximum allocation to organ 1, age class 1	---	---	---	38.3
PRAMX (2,1)	Maximum allocation to organ 2, age class 1	---	---	---	300
PRAMX (3,1)	Maximum allocation to organ 3, age class 1	---	---	---	300
PRAMX (1,2)	Maximum allocation to organ 1, age class 2	---	---	---	123.3
PRAMX (2,2)	Maximum allocation to organ 2, age class 2	---	---	---	300
PRAMX (3,2)	Maximum allocation to organ 3, age class 2	---	---	---	300
PRBMN (1,1)	Minimum live biomass organ 1, age class 1	---	---	---	46.7
PRBMN (2,1)	Minimum live biomass organ 2, age class 1	---	---	---	390
PRBMN (3,1)	Minimum live biomass organ 3, age class 1	---	---	---	340
PRBMN (1,2)	Minimum live biomass organ 1, age class 2	---	---	---	0
PRBMN (2,2)	Minimum live biomass organ 2, age class 2	---	---	---	0
PRBMN (3,2)	Minimum live biomass organ 3, age class 2	---	---	---	0
PRBMX (1,1)	Maximum live biomass organ 1, age class 1	---	---	---	66.7
PRBMX (2,1)	Maximum live biomass organ 2, age class 1	---	---	---	420
PRBMX (3,1)	Maximum live biomass organ 3, age class 1	---	---	---	420

PRBMX (1,2)	Maximum live biomass organ 1, age class 2	---	---	---	0
PRBMX (2,2)	Maximum live biomass organ 2, age class 2	---	---	---	0
PRBMX (3,2)	Maximum live biomass organ 3, age class 2	---	---	---	0
FLIGNI (1,1)	Lignin fraction of component 1, stage 1	---	---	---	0.09
FLIGNI (2,1)	Lignin fraction of component 2, stage 1	---	---	---	0.004
FLIGNI (1,2)	Lignin fraction of component 1, stage 2	---	---	---	0.13
FLIGNI (2,2)	Lignin fraction of component 2, stage 2	---	---	---	0
FLIGNI (1,3)	Lignin fraction of component 1, stage 3	---	---	---	0.13
FLIGNI (2,3)	Lignin fraction of component 2, stage 3	---	---	---	0
HIMAX	Maximum harvest index	---	---	---	0.33
HIWSF	Fraction of aboveground biomass available for harvest	---	---	---	0.23
HIMON (1)	Harvest flag month 1	---	---	---	1
HIMON (2)	Harvest flag month 2	---	---	---	0
EFRGRN (1)	Efficiency of green plant residue incorporation month 1	---	---	---	0.5
EFRGRN (2)	Efficiency of green plant residue incorporation month 2	---	---	---	0.4
EFRGRN (3)	Efficiency of green plant residue incorporation month 3	---	---	---	0.4
VLOSSP	Volatilization loss parameter	---	---	---	0.07
FSDETH (1)	Shoot death rate parameter 1	---	---	---	0.03
FSDETH (2)	Shoot death rate parameter 2	---	---	---	0.13
FSDETH (3)	Shoot death rate parameter 3	---	---	---	0.07
FSDETH (4)	Shoot death rate parameter 4	---	---	---	386.6
FALLRT	Fall rate of aboveground biomass	---	---	---	0.12
RDRJ	Root death rate for juvenile roots	---	---	---	0.17

RDRM	Root death rate for mature roots	---	---	---	0.1
RDSRFC	Fraction of root surface in topsoil	---	---	---	0.14
RTDTMP	Root depth temperature index	---	---	---	2
CRPRTF (1)	Crop residue partitioning fraction for pool 1	---	---	---	0.17
CRPRTF (2)	Crop residue partitioning fraction for pool 2	---	---	---	0
CRPRTF (3)	Crop residue partitioning fraction for pool 3	---	---	---	0
MRTFRAC	Fraction of biomass lost through mortality	---	---	---	0.2
SNFXMX (1)	Maximum biological N fixation rate	---	---	---	0.005
DEL13C	Carbon isotope signature (δ13C ‰)	---	---	---	-15
CO2IPR (1)	CO2 input rate parameter	---	---	---	1.05
CO2ITR (1)	CO2 transport rate parameter	---	---	---	0.77
CO2ICE (1,1,1)	CO2 effect on crop growth factor 1	---	---	---	1.05
CO2ICE (1,1,2)	CO2 effect on crop growth factor 2	---	---	---	1
CO2ICE (1,1,3)	CO2 effect on crop growth factor 3	---	---	---	1
CO2ICE (1,2,1)	CO2 effect on crop growth factor 1, stage 2	---	---	---	1.05
CO2ICE (1,2,2)	CO2 effect on crop growth factor 2, stage 2	---	---	---	1
CO2ICE (1,2,3)	CO2 effect on crop growth factor 3, stage 2	---	---	---	1
CO2IRS (1)	CO2 interaction with respiration rate	---	---	---	1
CKMRSPMX (1)	Max response of C to K level 1	---	---	---	0.1
CKMRSPMX (2)	Max response of C to K level 2	---	---	---	0.15
CKMRSPMX (3)	Max response of C to K level 3	---	---	---	0.05
CMRSPNPP (1)	NPP response to management practice 1	---	---	---	0

CMRSPNPP (2)	NPP response to management practice 2	---	---	---	0
CMRSPNPP (3)	NPP response to management practice 3	---	---	---	1.25
CMRSPNPP (4)	NPP response to management practice 4	---	---	---	1
CMRSPNPP (5)	NPP response to management practice 5	---	---	---	4
CMRSPNPP (6)	NPP response to management practice 6	---	---	---	1.5
CGRESP (1)	Crop growth respiration coefficient 1	---	---	---	0.23
CGRESP (2)	Crop growth respiration coefficient 2	---	---	---	0.23
CGRESP (3)	Crop growth respiration coefficient 3	---	---	---	0.23
NO3PREF (1)	Nitrate preference index	---	---	---	0.33
CMIX	Soil mixing factor	---	---	---	0.5
TMPGERM	Temperature for germination	---	---	---	10
DDBASE	Degree days base value	---	---	---	1500
TMPKILL	Temperature threshold for crop killing	---	---	---	7
BASETEMP	Base temperature for plant development	---	---	---	10
BASETEMP (2)	Alternate base temperature	---	---	---	30
MNDDHRV	Minimum days to harvest	---	---	---	10
MXDDHRV	Maximum days to harvest	---	---	---	20
CURGDYS	Current growing days	---	---	---	120
CLSGRES	Crop litter surface respiration coefficient	---	---	---	0.5
CMXTURN	Maximum C turnover rate	---	---	---	0.12
WSCOEF (1)	Water stress coefficient 1	---	---	---	0.378
WSCOEF (2)	Water stress coefficient 2	---	---	---	9
NPP2CS (1)	Conversion of NPP to carbon stock	---	---	---	1
CAFUE	Carbon allocation function unit efficiency	---	---	---	2
Favail (1)	Fraction of available nutrients 1	---	---	---	0.15

Favail (3)	Fraction of available nutrients 3	---	---	---	0.3
Favail (4)	Fraction of available nutrients 4	---	---	---	0.4
Favail (5)	Fraction of available nutrients 5	---	---	---	0.5
Favail (6)	Fraction of available nutrients 6	---	---	---	0.6
EMAX	Maximum evapotranspiration rate	---	---	---	1.35

Parameter	**Description**	**Default**	**Present study value**	**Reference**
			---*All sites*---	
FIX.100				
DEC 3 (1)	Decomposition rate of surface organic matter with active turnover.	6.0	7.0	Althoff et al. (2018); Araújo Neto et al. (2021)
DEC 3 (2)	Decomposition rate of soil organic matter with active turnover.	7.3	6.5	Althoff et al. (2018); Araújo Neto et al. (2021)
DEC 4	Decomposition rate of soil organic matter with slow turnover.	0.0045	0.0070	Althoff et al. (2018); Araújo Neto et al. (2021)
DEC 5	Decomposition rate of soil organic matter with passive turnover.	0.2	0.3	Althoff et al. (2018); Araújo Neto et al. (2021)
VARAT11 (1.1)	Maximum C/N ratio for material entering surface.	15	10	Araújo Neto et al. (2011)
VARAT3 (1.1)	Maximum C/N ratio for material entering som3.	11	9.5	Araújo Neto et al. (2011)
VARAT3 (2.1)	Minimum C/N ratio for material entering som3.	6	2	Araújo Neto et al. (2011)
CO2PPM (1)	Initial parts per million for CO2 effect.	350	418.24*	Locatelli et al. (2025); Meinshausen et al. (2020)
CO2PPM (2)	Final parts per million for CO2 effect.	700	563.92**	Locatelli et al. (2025); Meinshausen et al. (2020)

CO2PPM (2)	Initial parts per million for CO2 effect.	700	743.66***	Locatelli et al. (2025); Meinshausen et al. (2020)

*Value used for simulations considering the current scenario; ** Value used for simulations considering the SSP2-4.5 scenario; ***Value used for simulations considering the SSP5-8.5 scenario.

Table S3. Simulated (DayCent) and literature reported and measured values for Petrolina – PE, Betânia do Piauí – PI, and Sobral – CE, located in the *Brazilian drylands* region.

Site	Land use	Crop	Simulated value	Literature average	Reference
			--------kg MS ha⁻¹------		
Petrolina (PE)	Pastureland	*Buffel grass*	4.400	4.500 (±1.700)	Albuquerque et al., (1994); Moreira et al., (2007); Oliveira, (1993); Oliveira, (2005); Silva et al., (1987)
Betânia do Piauí (PI)	CLI (I)	*Buffel grass + Sorghum*	6.600	6.300 (±1.400)	Silva (2019); Souza & Espíndola, (1999)
	CLI (II)	*Buffel grass + Sorghum*	6.800	6.300 (±1.400)	
Sobral (CE)	Intercropping	*Maize + Massai grass*	6.500	7.300 (±500)	Silva et al., (2015)
	CLFI 10	*Sorghum + Massai grass*	6.800	7.000 (±1.400)	Embrapa measured field data
	CLFI 20	*Sorghum + Massai grass*	6.900	7.000 (±1.400)	Embrapa measured field data

*CLFI: Integrated livestock-crop-forest. Buffel grass (*Cenchrus ciliaris*). Sorghum (*Sorghum bicolor*). Maize (*Zea mays*). Massai grass *(Megathyrsus maximus*). DM: Dry matter.

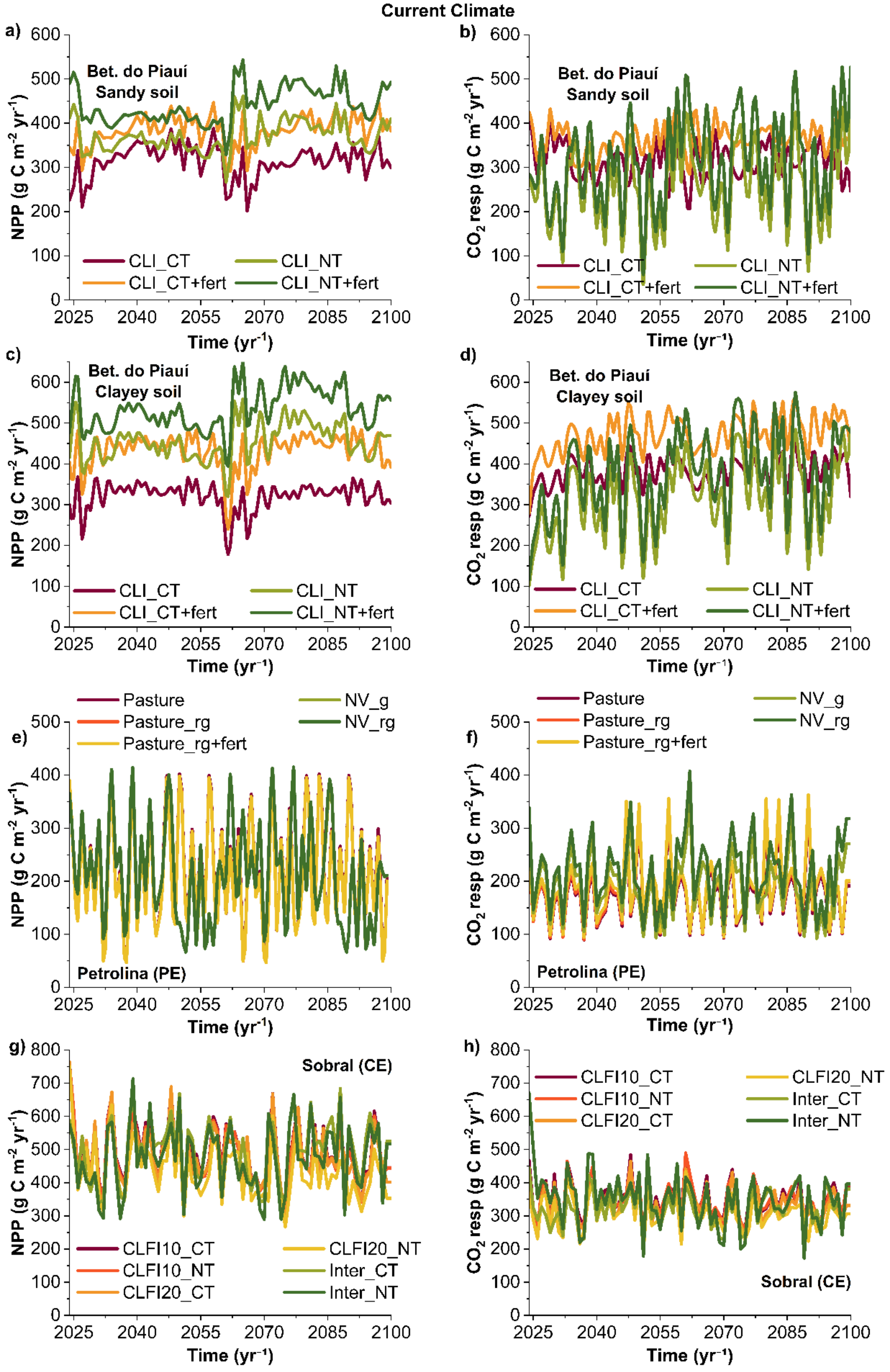

Fig. S5: Net productivity primary (NPP – Summation of all production values) and heterotrophic CO$_2$ respiration (CO2resp) to current climate data.

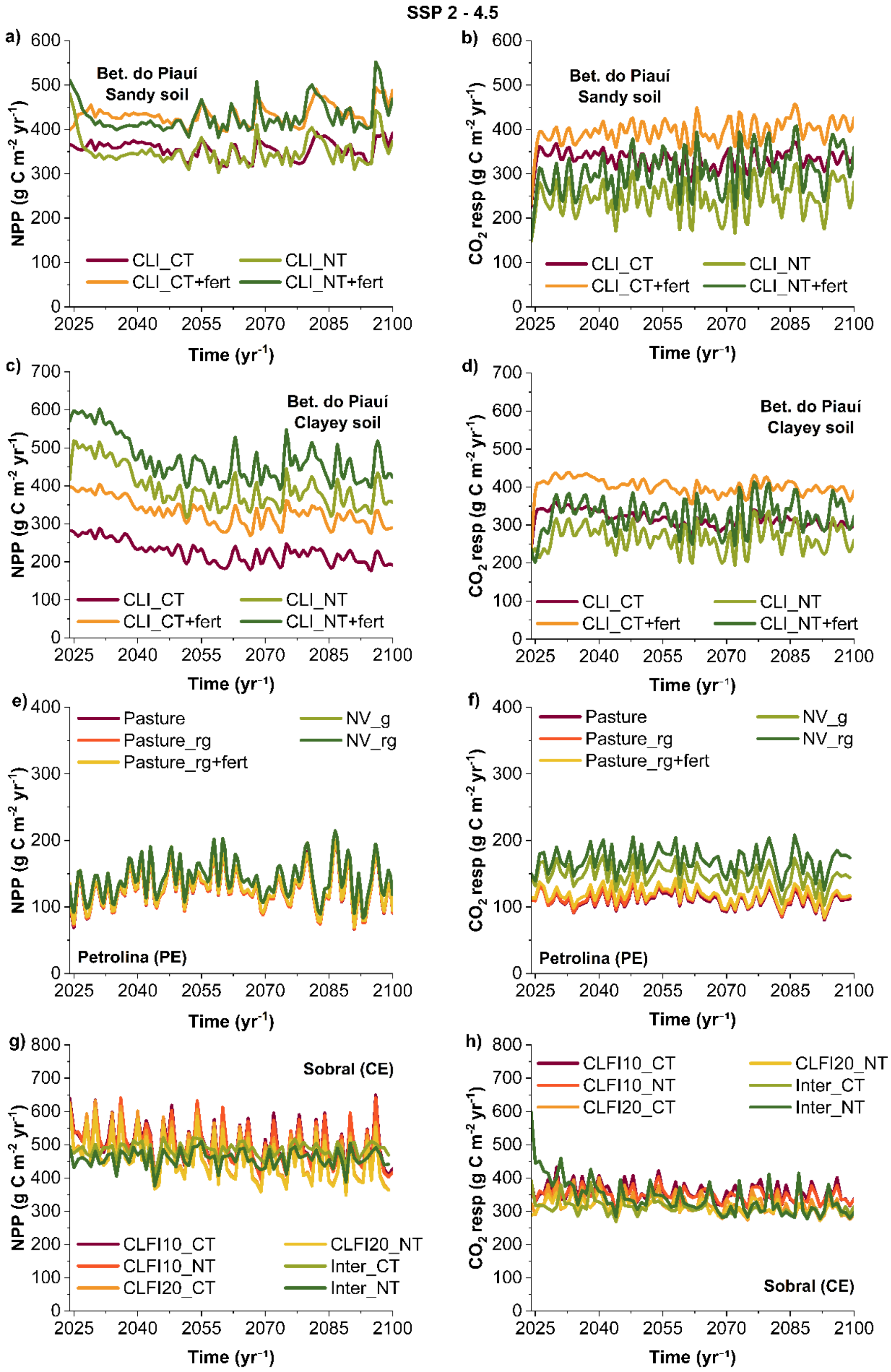

Fig. S6: Net productivity primary (NPP – Summation of all production values) and heterotrophic CO_2 respiration (CO2resp) to SSP 2 – 4.5 climate scenarios projected.

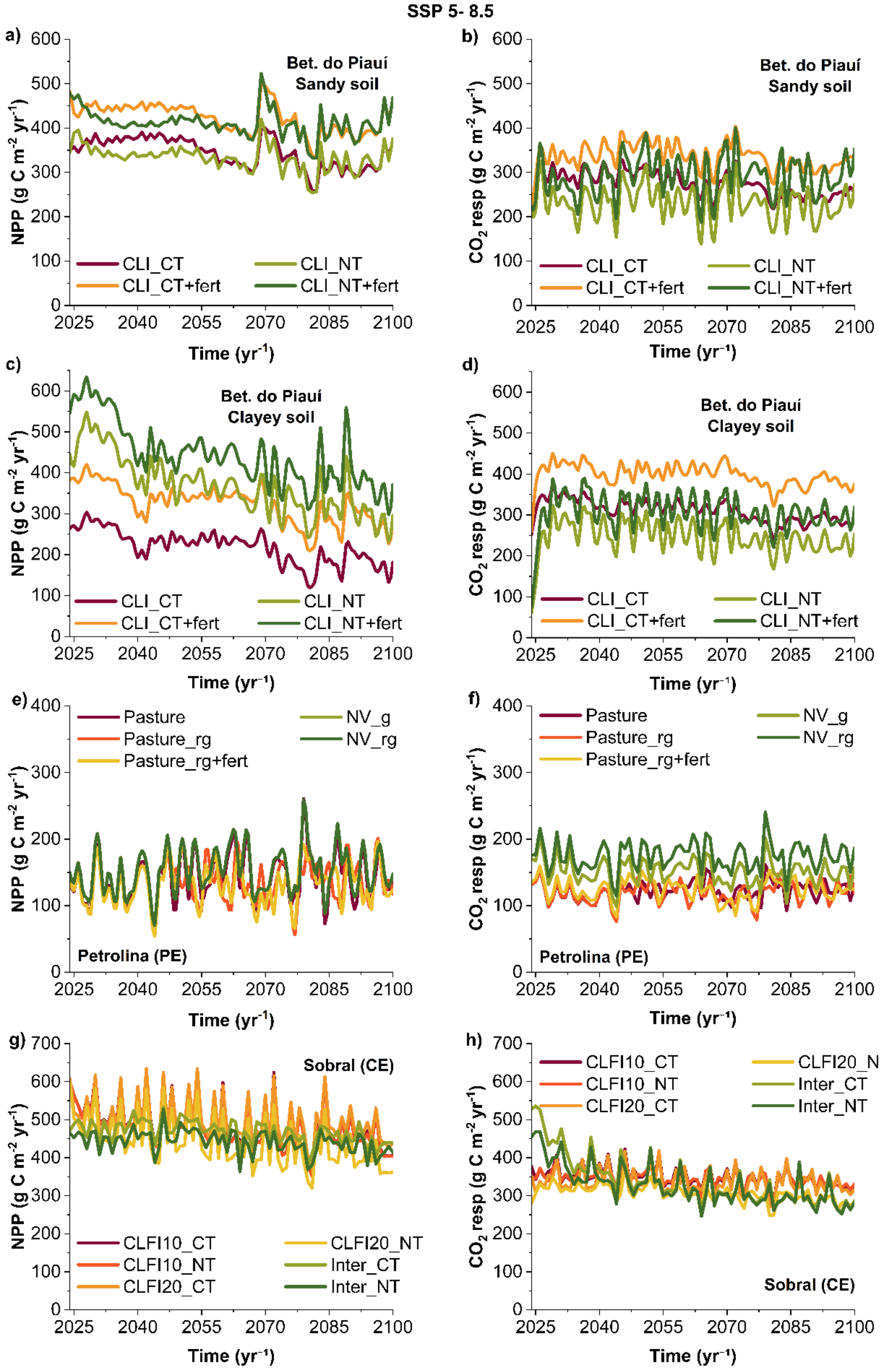

Fig. S7: Net productivity primary (NPP – Summation of all production values) and heterotrophic CO_2 respiration (CO2resp) to SSP 5 – 8.5 climate scenarios projected.

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