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Climate change projections and their impact on grassland systems: a longitudinal study in central Spain

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Abstract
Grassland systems are one of the most important ice-free ecosystems on Earth. They are important suppliers of ecosystem services such as carbon sequestration, biodiversity support, or pollination. However, in the last decades, there has been evidence of climate change linked to higher temperatures and reduced precipitation. In this study, we provide insight into the long-term dynamics of grassland systems that could help guide sustainable management. Grasslands in Spain are commonly located in the northern regions but also extend inland, where herbaceous and shrubby vegetation have adapted to thrive despite water scarcity conditions. Our study targets the region of Madrid, at the heart of the Iberian Peninsula, where grasslands cover almost 41% of territory. With reference to the Sixth Assessment Report from the Intergovernmental Panel on Climate Change, we established a 5×5 km grid to assess the proportion of grassland coverage. We employed proximity to a soil pit and a minimum grassland coverage of 40% within each grid cell as selection criteria. We gathered daily historical climate data on temperature and precipitation from 1950 to 2014 and future projections from 2015 to 2100. The future projections were SSP-4.5 and SSP-8.5 scenarios based on Shared Socioeconomic Pathways. First, we used MODIS data (2000–2024) to identify grassland coverage anomalies. Then, we applied the SIMPAST model, which required climate data, hydrological balance, solar radiation, and an initial seed count. Vegetation species were identified from September to May 2024–2025.

Introduction

Grasslands provide essential ecosystem services such as forage production, carbon sequestration, and biodiversity maintenance. They support extensive livestock systems and contribute to ecological stability. Additionally, they act as carbon sinks, regulate the hydrological cycle, and serve as habitats for diverse plant and animal species (Bengtsson et al. 2019). Shaped by climate and human activity, Madrid's grasslands host a mix of herbaceous and woody species, creating ecologically valuable landscapes with notable differences between the north and south. However, their dynamics are highly sensitive to climatic, edaphic, and hydrological factors, as well as human management practices, making them vulnerable to climate change (Zhao et al. 2020). Projected climate trends for the Iberian Peninsula suggest rising temperatures, intensified heatwaves, and decreasing precipitation, leading to more frequent droughts and extreme weather events (Sanz-Elorza et al. 2003). These changes threaten water availability and ecosystem resilience, particularly in grasslands dependent on seasonal rainfall and soil moisture retention (Joyce et al. 2016). Such climatic shifts pose a major challenge to pasture productivity, a key resource for livestock. Reduced biomass and declining forage quality may jeopardize traditional grazing systems, increasing production costs and undermining economic sustainability, especially in extensive livestock farms that rely on natural pastures (Carozzi et al. 2022). Understanding the dynamics of herbaceous biomass under different climatic scenarios is crucial for developing sustainable adaptation and management strategies. The present study addresses this issue through an integrated approach that combines modeling based on climatic, edaphic, and hydrological data with fieldwork for the empirical characterization of herbaceous biomass. We selected three study areas representative of different environmental conditions within the Mediterranean environment at Central Iberian Peninsula: Buitrago del Lozoya (northern zone 975 m of altitude, influenced by a mountain climate), Colmenar Viejo (central zone 883 m, in the transition between *dehesa* (open forest pasture) and grassland systems), and Tielmes (southern zone 585 m, with a drier climate and greater agricultural pressure).

The study has the following main objectives: 1) Analyze the evolution of herbaceous biomass in relation to climatic and soil conditions. 2) Develop a predictive model to estimate pasture productivity under different climate change scenarios. 3) Provide information for livestock management and the conservation of herbaceous ecosystems.

Through this multidimensional approach, we aim to contribute to the design of climate change adaptation strategies and the optimization of pasture management, promoting the sustainability of agricultural systems and the conservation of ecosystem services associated with these ecosystems. Additionally, the results may be useful for the formulation of environmental management policies and informed decision-making in territorial planning and biodiversity conservation.

Methods

The study was conducted in three regions within the Community of Madrid, Spain, each selected for their distinct climatic and edaphic characteristics (Figure 1). These sites represent a gradient of environmental conditions, from humid mountain areas to semi-arid agricultural landscapes, allowing for an assessment of pasture biomass response to climate regimes. 1) Buitrago del Lozoya (North): A mountainous area with cooler temperatures, higher rainfall, and deeper soils that enhance drought resilience. 2) Colmenar Viejo (Central): A transitional zone with moderate precipitation and high sensitivity to drought, where land use and grazing influence pasture productivity. 3) Tielmes (South): The driest and warmest site, with shallow soils and low water retention, making it highly vulnerable to climate change impacts.

A process-based biomass simulation model, based on the SIMPAST framework (Etienne et al. 2008), was used to estimate pasture productivity under different climate scenarios. The model integrates climatic and edaphic variables to dynamically assess biomass production over a hydrological year. Climatic inputs include daily precipitation, maximum, minimum, and mean temperatures, as well as solar radiation and potential evapotranspiration, derived from six IPCC AR6 models (IPCC,2023) under four SSP scenarios

(SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) for 2021–2100, with historical data from 1975–2021 (Kriegler et al., 2014; Riahi et al., 2017). Edaphic factors such as soil water retention, field capacity, wilting point, and effective soil depth were incorporated to evaluate moisture availability and its influence on pasture dynamics.

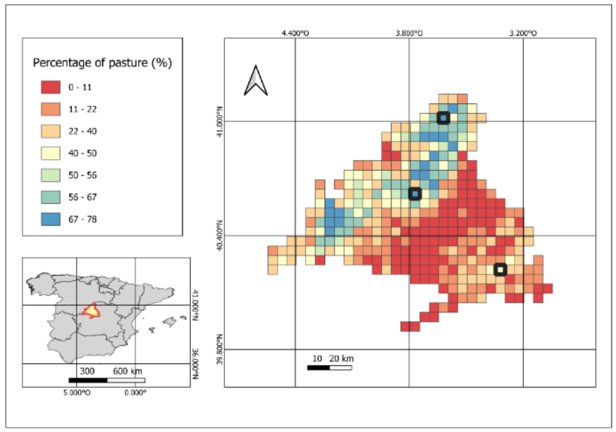

Figure 1. Geographic distribution of pasture percentage per pixel within the study area in the region of Madrid, Spain, derived from SIGPAC data and analyzed using QGIS (black circle).

The model calculates net primary productivity (NPP) and incorporates the leaf area index (LAI) as an indicator of vegetation cover. The hydrological balance is simulated by analyzing interactions between precipitation and soil moisture retention capacity, allowing for the assessment of biomass dynamics under historical and future climate conditions.

Results

Projected climate trends for the Madrid area (Spain) show a significant increase in annual mean temperature across all four SSP scenarios (Figure 2). By 2100, the highest-emission scenario (SSP5-8.5) suggests temperature increases exceeding 4 °C, while even the most optimistic scenario (SSP1-2.6) predicts warming above historical averages. These changes will likely intensify heatwaves and reduce seasonal thermal variability, impacting vegetation cycles and water availability.

Pasture biomass projections reveal strong spatial and temporal variability (Figure 3). The northern region (Buitrago del Lozoya) maintains relatively stable biomass levels due to higher precipitation and deeper soil. The central region (Colmenar Viejo) exhibits greater sensitivity to precipitation fluctuations, with biomass reductions during drought years. In contrast, the southern region (Tielmes) experiences the sharpest decline in biomass availability, highlighting its vulnerability to prolonged dry conditions and rising temperatures.

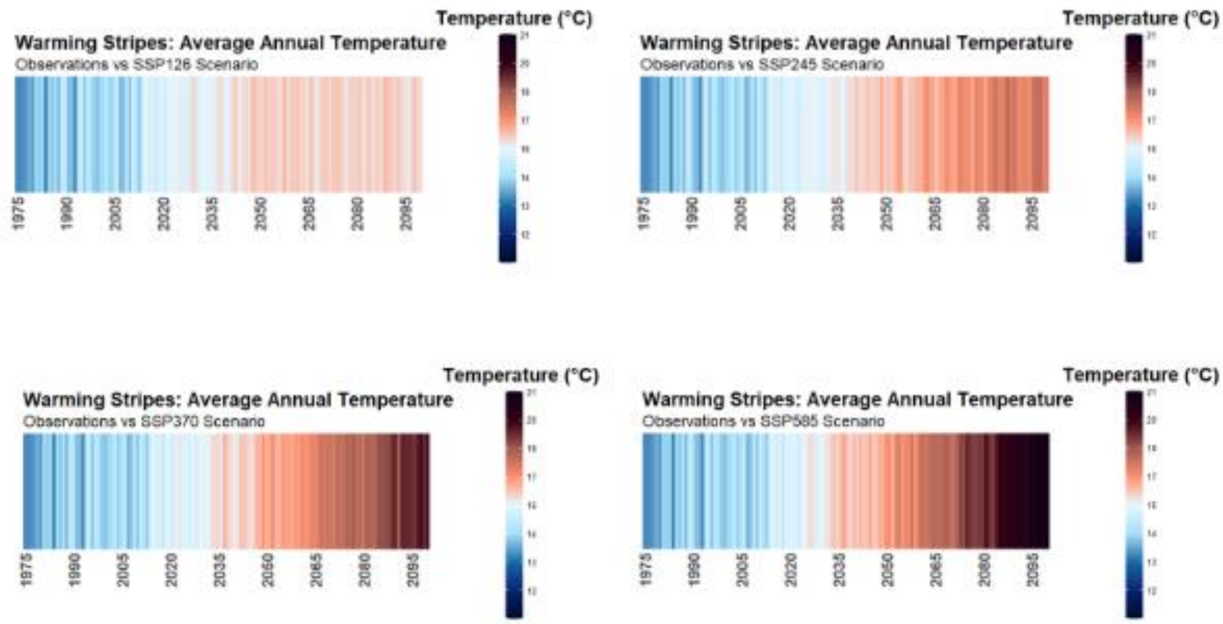

Figure 2. Annual mean temperature trends from 1975 to 2100 across the four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) in the region of Madrid, Spain (Central Iberian Peninsula).

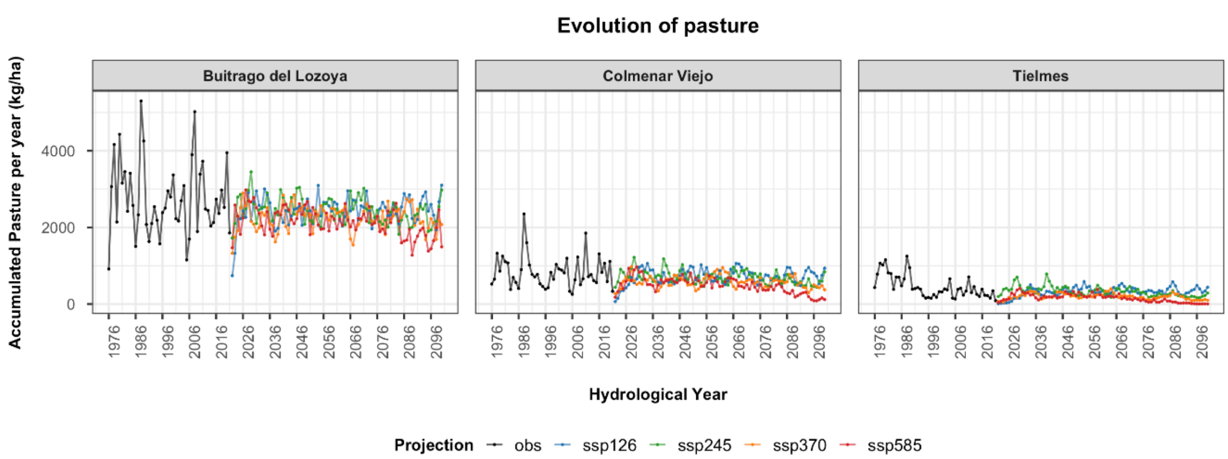

Figure 3. Temporal changes in simulated pasture biomass (dry matter) across the selected grids, showing interannual variability influenced by climate projections (Obs: observed climate; ssp126: SSP1-2.6, ssp245: SSP2-4.5, ssp370: SSP3-7.0, and ssp585 SSP5-8.5 scenarios).

Our results indicate that climate change will significantly affect pasture productivity, particularly in water-limited environments. While higher-altitude areas like Buitrago del Lozoya (North) may retain relatively stable biomass, warmer and drier regions such as Tielmes (South) will likely face severe reductions in forage availability. These findings align with previous studies on Mediterranean grasslands, where increasing aridity reduces primary productivity and alters species composition (Oesterheld et al. 1999; Peñuelas et al. 2007; Wang et al. 2022). This project highlights the importance of land management practices in mitigating productivity loss. Strategies such as adaptive grazing, improved soil conservation, and drought-resistant forage species may help sustain livestock systems under changing climatic conditions.

Conclusions and Implications

This study highlights the potential impacts of climate change on pasture productivity in the Madrid area of Central Spain, emphasizing regional differences in vulnerability. Northern grasslands may remain productive, while central and southern areas could experience substantial biomass reductions, affecting livestock sustainability. These findings underscore the need for adaptive management strategies to mitigate productivity losses and ensure the long-term viability of extensive livestock systems, key for economy and ecosystems. Future steps will include field validation through biomass sampling and species inventories, analysis of extreme events and integration of land management practices into the model as well as stakeholder engagement with local farmers and other land managers.

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