

# Impacts of Future Land Use on Vegetation CO<sub>2</sub> Fluxes Over Madrid, Spain

Roberto San Jose, Juan L. Perez-Camanyo and Miguel Jimenez-Gañan

**Abstract**—Biogenic CO<sub>2</sub> fluxes are influenced by temperature, radiation, and vegetation, which are represented by different land use types and affect CO<sub>2</sub> concentrations. High-resolution meteorological and land-use data were generated to model these factors. Vegetation indices were derived from the land use data and used to estimate biogenic emissions. These calculations were applied within three nested computational domains centred on Madrid (Spain). To assess the impacts of future land use on biogenic CO<sub>2</sub> emission fluxes, two simulations were conducted: R1, representing the socio-economic scenario of 2018 (baseline year), and R2, reflecting future socio-economic scenarios. The impacts were calculated by comparing the differences between R2 and R1. The research covered four climate and socio-economic scenarios: SSP126, SSP245, SSP370, and SSP585. This study is part of the EU-funded DISTENDER project, which aims to develop a methodological framework to integrate climate adaptation and mitigation strategies through participatory approaches. The findings indicate that changes in land use significantly affect biogenic CO<sub>2</sub> fluxes and concentrations. Conservation efforts under SSP1-2.6 increase CO<sub>2</sub> sequestration and lower concentrations, while rapid economic growth and deforestation under SSP5-8.5 lead to higher emissions and reduced sequestration capacity. The local climate, vegetation, and land use practices play a key role in shaping CO<sub>2</sub> flux dynamics.

**Keywords**—CO<sub>2</sub> sequestration, Climate mitigation, Vegetation indices.

## I. Introduction

Despite advances in understanding the global carbon cycle, local CO<sub>2</sub> sources and sinks remain poorly understood. Accurately quantifying CO<sub>2</sub> exchange is challenging due to its spatial and temporal variability, especially at the local level. Complex land-use patterns and diverse emission sources result in highly variable CO<sub>2</sub> fluxes between regions, making accurate quantification difficult without detailed local climate data [1]. In addition, biogenic CO<sub>2</sub> fluxes, which vary with climatic conditions, contribute to fluctuations in atmospheric CO<sub>2</sub> levels, increasing uncertainty in local estimates [2]

Global climate models (GCMs) are essential for projecting future climate scenarios and understanding the wider effects of greenhouse gas emissions, but their low spatial resolution limits their ability to capture detailed processes at regional and urban scales. Regional climate models (RCMs) are therefore used to downscale GCM out-puts, providing higher resolution data that better represent local climate dynamics (IPCC AR6).

This is especially important in areas with complex terrain or diverse surface features, where localized climate events can significantly influence CO<sub>2</sub> fluxes and transport. The Weather Research and Forecasting (WRF) model, combined with the Chemistry (Chem) model and the Vegetation Photosynthesis and Respiration Model (VPRM), is a powerful tool for simulating CO<sub>2</sub> transport and flux exchanges between the biosphere and the atmosphere. This integrated system allows researchers to quantify CO<sub>2</sub> sources, sinks and concentrations with high spatial and temporal resolution, taking into account climatic conditions. This information is crucial for understanding regional carbon cycles and assessing the effectiveness of mitigation strategies [3].

The study focuses on four CMIP6 climate and socio-economic scenarios: SSP126, SSP245, SSP370 and SSP585, ranging from low-emission trajectories that align with the Paris Agreement targets to high-emission scenarios that could lead to severe climate impacts.

The Shared Socioeconomic Pathways (SSP) framework presents a series of narratives or “storylines” that describe the likely future evolution of the world's population, economy, energy systems, culture and land use. These narratives are used in climate modeling to project how different socioeconomic pathways may influence greenhouse gas (GHG) emissions and cause climate change. However, while SSPs provide global-scale projections, effective climate policy and land management requires translating these broad narratives to finer local scales. This is especially important for understanding and managing land use changes and their effects on local ecosystems and biogenic carbon dioxide (CO<sub>2</sub>) fluxes.

DISTENDER findings will be made available through a Decision Support System (DSS), which will provide policy makers with essential tools to select the most appropriate strategies to manage climate risks in each case study. The estimation of bio-genic CO<sub>2</sub> fluxes is a crucial component for developing and evaluating mitigation strategies, linking directly to the objectives of the DISTENDER project.

## II. Methodology

In this study, we adopt a set of well established physics options consistent with those used in previous research [4]. These options include:

- Lin's microphysics scheme: The Lin microphysics scheme is used to simulate cloud formation, precipitation processes, and interactions between water vapor, cloud droplets, and ice particles. This scheme is essential to accurately represent cloud dynamics and their impact on trace gas concentrations.

- RRTMG radiation scheme: Both longwave and shortwave radiative processes are modeled using the Rapid Radiative Transfer Model for Global Circulation Models (RRTMG) scheme. This scheme provides a detailed representation of how radiation interacts with the atmosphere, influencing temperature and, consequently, chemical reactions and transport processes within WRF-Chem.

- Monin-Obukhov surface layer scheme: The Monin-Obukhov surface layer scheme is used to simulate the exchange of momentum, heat and moisture between the atmosphere and the Earth's surface. This parameterization is vital for accurately modeling surface boundary conditions that influence CO<sub>2</sub> fluxes.

- Yonsei University Planetary Boundary Layer Scheme: The Yonsei University (YSU) planetary boundary layer scheme is used to model the vertical mixing of atmospheric components within the boundary layer. This scheme effectively simulates the dynamics of the boundary layer, which is crucial for the dispersion and concentration of trace gases.

- Noah land surface model: The Noah land surface model simulates soil moisture, temperature and other land surface processes. It interacts closely with the VPRM to provide accurate biophysical conditions for calculating CO<sub>2</sub> fluxes.

- Grell-3D cloud parameterization: The Grell-3D cloud parameterization scheme is applied to represent subgrid-scale cloud processes, including convection. This scheme is essential to capture cloud impacts on radiation and, consequently, on atmospheric chemistry and transport.

The model focuses on the concept of Net Ecosystem Exchange (NEE) of CO<sub>2</sub>, which represents the net flux of carbon dioxide between the land surface and the atmosphere.

NEE is calculated (equation 1) as the difference between Gross Primary Production (GPP) - the total amount of CO<sub>2</sub>

absorbed by plants during photosynthesis - and ecosystem respiration, which is the release of CO<sub>2</sub> to the atmosphere through biological processes.

$$NEE = -GPP + Respiration \quad (1)$$

This equation highlights that NEE is negative when CO<sub>2</sub> uptake (GPP) exceeds respiration, indicating that the ecosystem is acting as a carbon sink. Conversely, a positive NEE value indicates that the ecosystem is a net source of CO<sub>2</sub>.

The respiration component in VPRM is parameterized by Equation (2):

$$Respiration = \alpha T_{air} + \beta \quad (2)$$

$\alpha$  and  $\beta$  are respiration parameters. These parameters have been optimized specifically for European ecosystems [5]. The dependency on air temperature reflects the temperature sensitivity of biological respiration processes, with higher temperatures generally leading to increased respiration rates.  $T_{air}$  is the air temperature.

Gross Primary Production (GPP) in VPRM is simulated using a combination of environmental and vegetation-specific parameters, as outlined in Equation (3):

$$GPP = (\lambda T_s W_s P_s) FAPAR_{PAV} \frac{1}{1 + \frac{PAR}{PAR_0}} PAR \quad (3)$$

In this equation:

$\lambda$ , represents the maximal light utilization efficiency, which is the ratio of CO<sub>2</sub> assimilation to the photosynthetic photon flux density.

$T_s$ , is the temperature sensitivity of photosynthesis, derived from air temperature.

$W_s$ , denotes water stress, calculated from the Land Surface Water Index (LSWI),

$P_s$ , represents the effect of leaf age on photosynthesis, also derived from LSWI, reflecting the seasonal variation in photosynthetic capacity.

FAPAR<sub>PAV</sub> is the fraction of absorbed photosynthetically active radiation, which correlates closely with the Enhanced Vegetation Index (EVI) derived from satellite data.

PAR is the photosynthetically active radiation, which is simulated from the shortwave radiation (SW) data provided by the WRF model, with the relationship  $SW \approx 0.505 \times PAR$

PAR<sub>0</sub> is a reference value for PAR, representing the half-saturation point where photosynthesis is at half its maximum rate.

The model uses vegetation indices such as the Enhanced Vegetation Index (EVI) and the Land Surface Water Index (LSWI), which are derived from satellite data to provide up-to-date information on vegetation health and water availability. These indices are calculated from the MODIS surface reflectance product, specifically using the MOD09A1 version 6 dataset. This dataset provides global coverage at a spatial resolution of 500 meters, with data updated every 8 days. As part of the Level 3 (L3) global gridded products, MOD09A1 is pre-processed to correct for atmospheric effects such as gases, aerosols and Rayleigh scattering, ensuring that the reflectance data accurately reflect land surface conditions, making it reliable for generating vegetation indices.

One of the key uses of Demeter is the downscaling of land use projections from the Global Change Assessment Model (GCAM) [6]. GCAM generates predictions of land use change

in up to 39 different land cover categories, known as GCAM land cover types (GLTs). Demeter then disaggregates these projections into a detailed spatial representation of land use change.

In this study, we used Demeter [7] to create a downscaled projection of GCAM global land use data [8] at a resolution of  $0.008^\circ \times 0.008^\circ$  for the period from 2015 to 2050, with updates every five years. These projections were based on four CMIP6 scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, and classified land cover into 18 different types using the MODIS classification system, commonly employed in models such as Weather Research and Forecasting (WRF). GCAM provides projections for 39 land cover types, and Demeter ensures that they are accurately disaggregated into specific grid cells for each category [9].

Our study follows similar conversion rules and restrictions as those described by [10], although we used a different land use classification system and higher spatial resolution to meet the unique objectives of our research. These adjustments allowed us to gain a more detailed and accurate understanding of land use changes and their potential effects on carbon sequestration and emissions.

R1 and R2a simulations use the same climate data, so differences in results highlight the impact of land use changes. In R1, CO<sub>2</sub> emissions change only due to climate variations,

while in R2, both climate and land-use changes affect emissions. The difference between R2 and R1 reveals the effect of land-use changes only on CO<sub>2</sub> emissions.

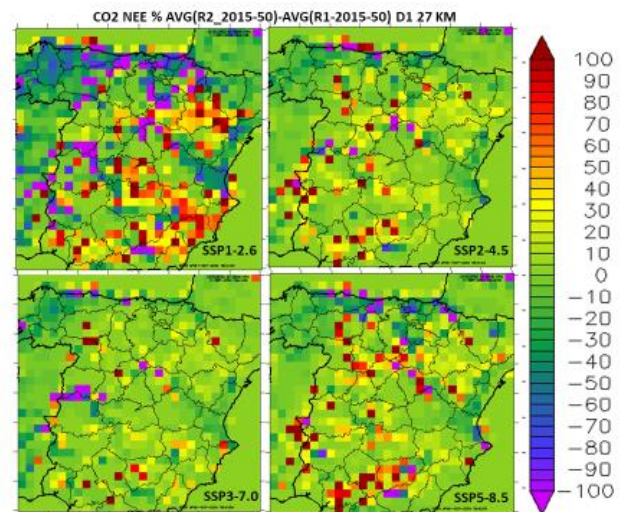
The modelling system was applied to assess CO<sub>2</sub> fluxes in the Madrid region, which covers part of the Iberian Peninsula, which is important for studying carbon dynamics due to its diverse land use and climate. A two-way nesting technique was used to perform high-resolution simulations on three grids with horizontal resolutions of 27 km, 9 km and 3 km. This setup provided detailed data for both the Iberian Peninsula and Madrid. The model also included 33 vertical layers to capture the distribution of CO<sub>2</sub> in the atmosphere.

### III. Results

Figure 1 shows the spatial distribution of the average effects (%) on biogenic CO<sub>2</sub> fluxes, calculated by comparing time-averaged values from 2015 to 2019 in simulations R2 and R1 over domain 1, representing the Iberian Peninsula, centered on the city of Madrid, with a spatial resolution of 27 km. The only difference between simulations R2 and R1 lies in the SSP scenarios, meaning that the observed differences directly reflect the impact of these scenarios on net biogenic

CO<sub>2</sub> fluxes. Negative values in the figure indicate improvements, either through increased carbon sequestration or reduced emissions, while positive values indicate a worsening, with increased CO<sub>2</sub> emissions or reduced sequestration. Impacts are spatially spread across the domain, depending on the land uses projected for each scenario.

In the SSP1-2.6 scenario, there is a clear improvement in biogenic CO<sub>2</sub> emissions. Biogenic CO<sub>2</sub> fluxes are expected to increase significantly in the north western, more vegetated region, but some increase (or reduction in uptake) of emissions is observed in the southwest. SSP2-4.5 and SSP3-7.0 scenarios show more moderate effects, with less drastic changes in emissions or sequestration. The worst deterioration occurs in SSP5-8.5, where emissions increase significantly and improvements observed in northern mountainous areas in other scenarios disappear, with much of the region showing worsening CO<sub>2</sub> emissions. These results align with the trends projected in EVI and LSWI for each SSP scenario, providing valuable insights into the spatial distribution of impacts and allowing for a detailed assessment of how different future socio-economic pathways may affect biogenic CO<sub>2</sub> fluxes across regions.



**Fig. 1. Average impact (%) of the four Shared Socioeconomic Pathways (SSPs) on the Net Ecosystem Exchange (biogenic CO<sub>2</sub> fluxes) in the Iberian Peninsula, simulated at a 27 km spatial resolution (D1).**

Figure 2 clarifies the impacts of the four Tier 1 scenarios on average CO<sub>2</sub> concentrations, with a focus on biogenic emissions, holding anthropogenic emissions and boundary conditions constant in the R1 and R2 simulations. This methodological approach facilitates the isolation of biogenic

processes, thus allowing a clearer understanding of the mechanisms driving changes in CO<sub>2</sub> levels.

The results are derived from high-resolution simulations performed at 3 km over the city of Madrid. The attached maps reveal remarkable spatial distributions that distinguish the scenarios, with discernible similarity between SSP1-2.6 and SSP3-7.0, as well as between SSP2-4.5 and SSP5-8.5. In the first group (SSP1-2.6 and SSP3-7.0), reductions in CO<sub>2</sub> concentrations are prominent in the north-western region, while increases are observed in the south-eastern areas. Regions experiencing increased CO<sub>2</sub> concentrations are predominantly agricultural, highlighting the impact of land-use practices that tend to generate higher emissions. In contrast, areas characterised by decreasing CO<sub>2</sub> levels are mainly associated with vegetation-rich land uses, which effectively sequester carbon.

Particularly noteworthy is the SSP1-2.6 scenario, where the most pronounced positive and negative impacts on CO<sub>2</sub> concentrations are observed. In contrast, the second set of scenarios (SSP2-4.5 and SSP5-8.5) shows that the most significant increases in CO<sub>2</sub> concentrations occur in the SSP5-8.5 scenario, with average increases reaching up to 0.18 % from 2019 to 2050.

These spatial patterns underline the key role of land cover and vegetation density in shaping the distribution of CO<sub>2</sub> concentrations in prospective future scenarios. The findings emphasise the need for specific land management and conservation strategies aimed at increasing vegetation density and maintaining carbon sinks, which are essential for mitigating biogenic CO<sub>2</sub> emissions and meeting the challenges posed by climate change.

**Fig. 2. Average impact (%) of the four Shared Socioeconomic Pathways (SSPs) on CO<sub>2</sub> concentrations in the Madrid city, simulated at a 3 km spatial resolution (D3).**

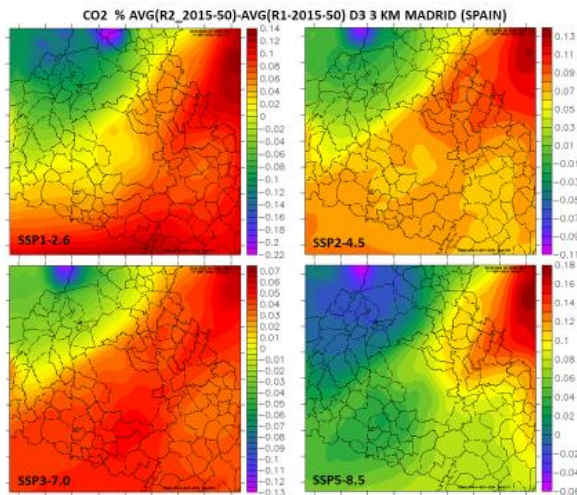
#### IV. Conclusions

The SSP1-2.6 scenario projections indicate a significant increase in EVI due to conservation efforts, while SSP5-8.5 shows a sharp decrease in vegetation cover due to urbanisation and resource extraction. The difference between the R1 and R2 simulations highlights the significant effects of land use change on CO<sub>2</sub> emissions. The SSP1-2.6 scenario leads to substantial improvements in biogenic CO<sub>2</sub> emissions, while the SSP5-8.5 scenario exacerbates emissions significantly. The Iberian Peninsula is projected to function as a net carbon sink, with increased CO<sub>2</sub> absorption rates attributed to improved vegetation and management practices. However, localised increases in emissions are observed in agricultural areas, with the distribution of CO<sub>2</sub> concentrations varying significantly depending on the scenario, with vegetation-rich areas showing lower CO<sub>2</sub> levels, underlining the importance of land cover in carbon sequestration.

The results reinforce the need to adapt land management strategies to maintain carbon sinks and mitigate emissions, providing crucial information for policy makers involved in climate risk management. This high-resolution assessment underlines the critical interaction between land use changes and biogenic CO<sub>2</sub> emissions in urban settings, highlighting the importance of strategic land management in addressing climate challenges. The results provide valuable guidance for effective mitigation strategies tailored to local contexts, in line with the broader objectives of the DISTENDER project.

#### Acknowledgment

The UPM authors acknowledge the computer resources and technical assistance provided by the Centro de Supercomputación y Visualización de Madrid (CeSViMa). The UPM authors thankfully acknowledge the computer resources, technical expertise and assistance provided by the Red Española de Supercomputación. DISTENDER has received funding from the European Union’s Horizon EU research and innovation programme under grant agreement No 101056836”.



## References

- [1] G. Eason, B. Noble, and I. N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," *Phil. Trans. Roy. Soc. London*, vol. A247, pp. 529–551, April 1955. (*references*)
- [2] McHale MR, Hall SJ, Majumdar A, Grimm NB. Carbon lost and carbon gained: a study of vegetation and carbon trade-offs among diverse land uses in Phoenix, Arizona. *Ecological Applications*. 2017 Mar;27(2):644–61.
- [3] Lei N, Han J. Effect of precipitation on respiration of different reconstructed soils. *Scientific Reports* [Internet]. 2020 Apr 30 [cited 2021 Nov 22];10:7328. Available from: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7193616/>
- [4] Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*. 2016 May 26;9(5):1937–58.
- [5] Fast JD, Gustafson WI, Easter RC, Zaveri RA, Barnard JL, Chapman E, et al. Evolution of ozone, particulates, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology-chemistry-aerosol model. *Journal of Geophysical Research*. 2006 Nov 16;111(D21).
- [6] Mahadevan P, Wofsy SC, Matross DM, Xiao X, Dunn AL, Lin JC, et al. A satellite-based biosphere parameterization for net ecosystem CO<sub>2</sub> exchange: Vegetation Photosynthesis and Respiration Model (VPRM). *Global Biogeochemical Cycles*. 2008 Apr 12;22(2):n/a-n/a.
- [7] R. San José, J. Mercado Pérez, Balzarini A, Rocío Baró, Curci G, Forkel R, et al. Sensitivity of feedback effects in CBMZ/MOSAIC chemical mechanism. *Atmospheric Environment*. 2015 Aug 1;115:646–56.
- [8] Vernon CR, Yannick Le Page, Chen M, Huang M, Calvin KV, Kraucunas IP, et al. Demeter – A Land Use and Land Cover Change Disaggregation Model. *Journal of open research software*. 2018 Apr 20;6(1):15–5.
- [9] Calvin K, Patel P, Clarke L, Asrar G, Bond-Lamberty B, Cui RY, et al. GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development* [Internet]. 2019 [cited 2020 Jun 30];12(2):677–98. Available from: <https://www.mendeley.com/catalogue/25fc15a1-d858-39f1-9b0c-d3e3b129f101/>
- [10] Chen M, Vernon CR, Graham NT, Hejazi M, Huang M, Cheng Y, et al. Global land use for 2015–2100 at 0.05° resolution under diverse socioeconomic and climate scenarios. *Scientific Data*. 2020 Oct 2;7(1).



ROBERTO SAN JOSE completed his PhD in 1982 related to the unstable surface turbulent boundary layer parameterization. He has been involved in air pollution modelling mainly using three-dimensional mesoscale models, such as MM5 and CMAQ. He created the Environmental Software and Modelling Group at Computer Science School of the Technical University of Madrid (UPM) in 1992. He spent one year at the Max-Planck Institute for Meteorology and two years at IBM-Bergen Environmental Sciences and Solution Centre. He has more than 150 publications in different national and international scientific journals. He has been a full professor since 2001.