



1 **National-Scale Inventory based Climate Impact Analysis of the Nitrogen Balance, including all Nitrogen**
2 **Fluxes using Process-Based Modelling with the LandscapeDNDC Model and EURO-CORDEX Ensembles**
3 **for Greece**

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20

21 **Abstract**

22 In this study, we have simulated inventories of arable production and soil carbon and nitrogen cycling on
23 a national scale (0.25 x 0.25-degree) for Greece with the bio-geochemical ecosystem model
24 LandscapeDNDC. Based on observation data, we have aggregated for each grid cell 4 most likely crop
25 rotations, including nitrogen and manure fertilization, tilling and irrigation. The arable management was
26 continuously projected into the future until 2100, while plant phenology was adapted to local conditions,
27 general properties of the arable management were kept constant into the future, such as the selection of
28 crops or the share of irrigated arable land. To understand the impacts of climate change, we used the
29 EURO-CORDEX-11 regional climate ensemble to drive the LandscapeDNDC impact model under scenarios
30 RCP4.5 (16 datasets) and RCP8.5 (32 datasets). The simulation timespan was from 1990 until 2100, using
31 the first 10 years as spin-up to obtain equilibrium in the model's internal carbon and nitrogen pools from
32 the model initialization.

33 Arable production declines from 2045 onwards by 9.5% or 144 kg C ha⁻¹ yr⁻¹ under RCP4.5 and by 29% or
34 484 kg C ha⁻¹ yr⁻¹ towards 2100. At present, the ensemble results show an average soil carbon loss of 122.1
35 kg C ha⁻¹ yr⁻¹ versus 139.7 kg C ha⁻¹ yr⁻¹ in the future. The gaseous outfluxes of the ensemble simulations
36 show N₂O emissions of 0.494 to 0.453 kg N₂O-N ha⁻¹ yr⁻¹, NO emissions of 0.031 kg NO-N ha⁻¹ yr⁻¹, N₂



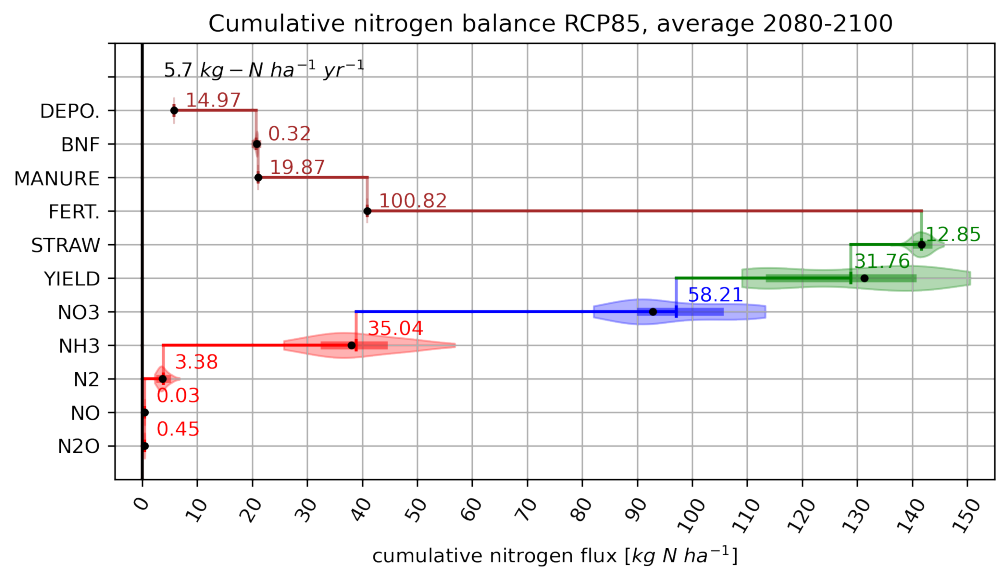
37 emissions of 4.806 to 3.377 kg N₂-N ha⁻¹ yr⁻¹, NH₃ emissions of 24.662 to 35.040 or 34.205 kg NH₃-N
38 ha⁻¹ yr⁻¹ and nitrate leaching losses from 54.304 to 58.213 kg NO₃-N ha⁻¹ yr⁻¹ comparing present versus
39 future conditions. The overall nitrogen balance of the ensemble simulations reveals a mean nitrogen loss
40 of 4.7 versus 5.7 kg-N ha⁻¹ yr⁻¹ comparing present to future conditions.
41



Highlights

- 21st century temperature increase of 1.37°C under RCP4.5 and 3.21°C under RCP8.5 from the ensembles
- Precipitation decreases of 17.96 mm for RCP4.5 and 102.52 mm under RCP8.5 from the ensembles
- Arable production decreases by 9.5% under RCP4.5 and by 29% under RCP8.5
- Ensemble results show a soil carbon loss of 122.1 under RCP4.5 versus 139.7 kg C ha⁻¹ yr⁻¹ under RCP8.5
- Ensemble simulations show averaged N₂O emissions of 0.494 for RCP4.5 and 0.453 kg N₂O–N ha⁻¹ yr⁻¹ under RCP8.5

Graphical abstract





60 1 Introduction

61 In a rapidly changing global climate, the intricate relationships within agroecosystems among crop
 62 production, biogeochemical cycles, and greenhouse gas emissions have emerged as focal points of
 63 scientific research. It also affects food security via direct and indirect effects such as agricultural
 64 productivity, e.g., via elevated atmospheric CO₂ concentrations, but also soil nutrient cycles, driven largely
 65 by increasing temperature trends but also extreme temperature exposures, altered precipitation regimes,
 66 drought patterns, and erosion, carbon nitrogen depletion, etc. Uncertainties related to the evolution of
 67 future socioeconomic pathways (SSP) and scientific uncertainties related to the incomplete knowledge of
 68 climate and agroclimatic processes contribute to the cascade of uncertainty in all climate impact studies
 69 and risk assessments (see Fig. 1 of Wilby & Dessai, 2010).

70 While our general understanding of these changes is high on a global level, the level of confidence in these
 71 projections varies from regional to local levels. Giorgi, (2006) reported the Mediterranean as a vulnerable
 72 region worldwide due to its high exposure to the effects of climate. The area is characterized by a high
 73 population density and high socioeconomic importance, as it sustains a large proportion of the European
 74 Food Production System.

75 General circulation models (GCMs) have been extensively used in the past to assess the changes in the
 76 state of climate, providing large-scale information on essential climate variables (Bojinski et al., 2014),
 77 although their spatial resolution is generally low (Nocentini et al., 2015; Yang & Villarini, 2021). Regional
 78 climate models (RCMs) can be used to enhance the spatial and temporal resolution of the GCM
 79 projections by conducting dynamical downscaling from a regional to a national level (Giorgi, 2006).
 80 Selecting a specific GCM/RCM model combination for a specific region for a climate projection may still
 81 be biased due to systematic model behaviors, possibly originating from either or both the GCM and the
 82 RCM (Eden et al., 2012) models. Therefore, it is advisable to use an ensemble of GCM/RCM climate
 83 projections to assess the climate change impact on a regional to local scale (Paeth et al., 2023).

84 While the approach of propagating ensembles of climate projections through models has already been
 85 used, e.g., in hydrology (Weiland et al., 2021) it has not been addressed with ecosystem models on the
 86 national scale, and studies addressing the full nitrogen balance are still very limited (Petersen et al., 2021);
 87 example of grassland on a local scale, and additionally examples of climate impact assessments with
 88 ensembles, full N balance in Austria (Schroeck et al., 2019), and Thessaly, an example in Greece by
 89 Sifounakis et al., (2024).

90 In this study, we aim to present national-scale assessments of the full nitrogen and carbon balance,
 91 including all associated fluxes of reactive and non-reactive nitrogen (such as NO, N₂, N₂O, NH₃ emissions,
 92 NO₃ leaching, N-in-yield, biological nitrogen fixation) of the cropland cultivation for Greece for present
 93 and future conditions on a national scale.

94 Besides the aforementioned, we also investigated the uncertainty due to climate change projections on
 95 the carbon and nitrogen modeling.



96 To obtain these results, we propagated the European climate dataset of the Coordinated Regional Climate
97 Downscaling Experiment (EURO-CORDEX) (Jacob et al., 2020) under the mid-impact and high-impact
98 Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5, respectively) through the
99 LandscapeDNDC model to compile result ensembles of detailed inventory simulations.
100 The following research questions are addressed in the study:

- 101 a) Assessment of the full nitrogen balance of the Greek cropland system for present conditions as
102 demanded by UN FCCC reporting
- 103 b) Climate change impact analysis on agricultural production on a national scale due to climate
104 change projections
- 105 c) Assessment of the soil carbon balance of the agricultural cropland system for present conditions
106 and future projections under climate change
- 107 d) Climate change impact analysis on the carbon and nitrogen cycle and fluxes towards 2100

108 The novelty of the study is the use of process-based modelling on a national scale for the first time to
109 address questions a) to d).



110 2 Material and Methods

111 2.1 Biogeochemical Model

112 Biogeochemical models, such as LandscapeDNDC (Haas et al., 2013), simulate the processes of carbon and
 113 nitrogen cycling in croplands based on model initialization with soil physical and chemical properties.
 114 Agricultural management and climate data need to be provided as boundary conditions to drive the model
 115 simulations forward in time.

116 LandscapeDNDC (Haas et al., 2013) is a modular, process-based ecosystem model designed to simulate
 117 biogeochemical changes in carbon (C) and nitrogen (N) within croplands, forests, and grasslands at both
 118 site-specific and regional scales. It integrates various modules related to plant growth, micro-
 119 meteorology, water cycling, as well as physico-chemical, plant, and microbial C and N cycling. Additionally,
 120 it models interactions between terrestrial ecosystems and the atmosphere and hydrosphere.
 121 LandscapeDNDC is a generalized framework for plant development and soil biogeochemistry, built upon
 122 the foundations of agricultural DNDC and Forest-DNDC models (Li, 2000). The model has been used and
 123 tested for Greek conditions in a previous study by Sifounakis et al. (2024) and was deployed in the same
 124 configuration.

125 To initialize LandscapeDNDC, site-specific physical and chemical soil profile data are utilized, including
 126 information at different soil depths. This data includes soil organic carbon (SOC) and nitrogen (SON)
 127 content, soil texture (proportions of clay, sand, and silt), bulk density, pH levels, saturated hydraulic
 128 conductivity, field capacity, and wilting point. Additionally, the model incorporates daily or hourly climate
 129 variables such as air temperature (maximum, minimum, and average), precipitation, solar radiation, air
 130 chemistry data related to dry and wet nitrogen deposition, and atmospheric CO₂ concentration.

131 Agricultural management practices, such as crop planting and harvesting, fertilization (both organic and
 132 synthetic), feed cutting, and tilling, are also integrated to drive LandscapeDNDC simulations. Crop growth
 133 is modeled using a temperature degree sum approach, incorporating CO₂ concentrations, while daily
 134 growth limitations due to water and nutrient availability, as well as drought stress, are also considered.

135 In this study, site-specific crop parameterizations were derived from a previous study by Sifounakis et al.,
 136 (2024). A detailed overview of the cultivated crops, crop rotations, fertilization practices, and manure
 137 application is provided in **Fehler! Verweisquelle konnte nicht gefunden werden.** (supplementary
 138 material).

139 2.2 National scale model input data

140 The national-scale input data sets for this modelling study were extracted from a previous study by Haas
 141 et al. (2022). The dataset decomposed Greece into 430 conformal 0.25° latitude x 0.25° longitude grid
 142 cells, each holding, e.g., profile information of soil physical and chemical properties for model initialization



143 based on the European Soil Database (ESDB, 2004). The grid cells were assigned their share of arable land
 144 based on the aggregation of Corine Landcover data, which assigned the diverse Greek land use into 3
 145 major agricultural classes: arable land, grassland, and forests. The resulting arable land class containing
 146 2.9 mio ha consists of cultivated agricultural (1.6 mio ha), agroforestry/tree plantations (1.0 mio ha),
 147 vineyards (0.1 mio ha), and the rest (fallow land, gardens, 0.2 mio ha)
 148 (ELSTAT: <https://www.statistics.gr/en/statistics/-/publication/SPG06/2023>, last access: February 2024).

149

150 2.2.1 Agricultural management

151 Agricultural management data to drive model simulations was available from Haas et al. (2022) for the
 152 period 1951-2100. For this study, we have aggregated this management data to the simulation period
 153 1990-2100, while the period 1990-2005 was used as a prerun period to achieve equilibrium for the soil
 154 carbon and nitrogen pools, and the evaluation period 2005-2100 was used for the climate impact
 155 assessment.

156 Synthetic fertilizer input originates from FAO statistics, and manure use was assessed from regional
 157 statistics of animal head numbers for main livestock classes (data adapted from Haas et al., 2022).

158 The arable land was divided into rainfed and irrigated land according to Mirca 2000 (Portmann et al.,
 159 2010) and national reports as used by (Sifounakis et al., 2024). Mirca lacks a projection of irrigation use
 160 into the future; thus, the assumptions on irrigation management were kept constant in this study. On a
 161 national scale, the share of rainfed versus irrigated cropland cultivation was 52/48 % (Sifounakis et al.,
 162 2024).

163 2.2.2 EURO-CORDEX regional climate data

164 In this study, we retrieve regional climate data from the EURO-CORDEX data repositories, with a spatial
 165 resolution of ~ 12 Km (0.11°). The various combinations of GCMs/RCMs are shown in Table 1. The 16/32
 166 model combinations consist of 6 GCMs, as well as 8 RCMs, comprising structural variability/uncertainty of
 167 climate change projections until 2100. The two climate change ensembles represent only subsets of the
 168 EURO-CORDEX ensembles. The EURO-CORDEX ensembles consist of more climate change projections, but
 169 due to constraints in data availability for download from the various data centers/repositories and
 170 completeness for all necessary variables, we had to limit the study to the climate change projections
 171 summarized in Table 1 at the start of this study. Note that 14 GCM/RCM combinations are common in
 172 both RCPs, while the RCP4.5 ensemble contains 2 unique combinations not present in the RCP8.5, and the
 173 RCP8.5 ensemble contains 18 unique combinations not present in the RCP4.5 ensemble.

174 At first, the model data was bilinearly interpolated to match the 0.25×0.25 -degree spatial resolution of
 175 the simulation grid. The interpolated variables used to drive the LandscapeDNDC model were daily



176 averaged temperature (tas), daily maximum temperature (tasmax), daily minimum temperature (tasmin),
177 shortwave down global radiation (rsds), and precipitation flux (pr).



178

179 Table 1. Climate datasets obtained for the current study from EURO-CORDEX for medium (16
 180 representations for RCP4.5) and extreme scenarios (32 representations for RCP8.5), respectively. The
 181 datasets consist of a historical period (1951-2004) and the future climate change projection time spans
 182 (2005-2100). 14 GCM-RCM combinations are common in both RCPs, while RCP4.5 ensemble contains 2
 183 unique combinations, and the RCP8.5 ensemble contains 18 unique combinations. ¹⁾ global circulation
 184 model, ²⁾ regional climate model (for details, see Olschewski et al., 2024).

No.	Scenario	GCM ¹⁾	RCM ²⁾	common / unique
1	RCP4.5	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	common
2			KNMI-RACMO22E	common
3			SMHI-RCA4	common
4		ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	common
5			KNMI-RACMO22E	common
6			SMHI-RCA4	common
7		IPSL-CM5A-MR	SMHI-RCA4	common
8		MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	common
9			DMI-HIRHAM5	unique
10			KNMI-RACMO22E	common
11		MPI-ESM-LR	CLMcom-CCLM4-8-17	common
12			SMHI-RCA4	common
13			MPI-CSC-REMO2009	common
14		NCC-NorESM1-M	DMI-HIRHAM5	unique
15			SMHI-RCA4	common
16			GERICS-REMO2015	common
1	RCP8.5	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	common
2			CLMcom-ETH-COSMO-crCLIM-v1-1	unique
3			DMI-HIRHAM5	unique
4			KNMI-RACMO22E	common
5			SMHI-RCA4	common
6			GERICS-REMO2015	unique
7			ICTP-RegCM4-6	unique
8		ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	common
9			CLMcom-ETH-COSMO-crCLIM-v1-1	unique
10			DMI-HIRHAM5	unique
11			KNMI-RACMO22E	common
12			SMHI-RCA4	common
13			ICTP-RegCM4-6	unique
14		IPSL-CM5A-MR	DMI-HIRHAM5	unique
15			KNMI-RACMO22E	unique
16			SMHI-RCA4	common
17			GERICS-REMO2015	unique
18		MOC-HadGEM2-ES	CLMcom-CCLM4-8-17	common
19			CLMcom-ETH-COSMO-crCLIM-v1-1	unique
20			KNMI-RACMO22E	common
21			SMHI-RCA4	unique



22		MPI-ESM-LR	CLMcom-CCLM4-8-17	common
23			CLMcom-ETH-COSMO-crCLIM-v1-1	unique
24			DMI-HIRHAM5	unique
25			KNMI-RACMO22E	unique
26			SMHI-RCA4	common
27			MPI-CSC-REMO2009	common
28			ICTP-RegCM4-6	unique
29		NorESM1-M	CLMcom-ETH-COSMO-crCLIM-v1-1	unique
30			KNMI-RACMO22E	unique
31			SMHI-RCA4	common
32			GERICS-REMO2015	common

185

186

187 2.3 Climate Change Impact Assessment

188 Climate data was analysed for grid cells containing arable land over the study region. Thus, grid cells over
 189 the sea, neighboring countries, and non-cropland areas/land use (e.g., mountains) were excluded from
 190 the analysis.

191 For the climate impact analysis, we consider the present conditions at 2020, the 30-year time slice from
 192 2005 until 2034, and for future conditions, the time slice from 2070 until 2099. All spatial data
 193 aggregations were built using cropland area-weighted aggregations. All figures showing time series were
 194 using 10-year rolling means to reduce fluctuations. In general, when comparing model outcomes for the
 195 present and future, spatial and temporal means are assumed. These statistics were used and
 196 described/analyzed in section 3.4.

197 The analysis displays the chronological evolution of the carbon and nitrogen cycle components towards
 198 the end of the 21st century. We further quantify the impact of climate change on these components
 199 between current and future conditions.

200 2.3.1 Chronological evolution until the end of the 21st century

201 The biogeochemical model simulation results were analyzed for the period 2020 - 2100. Aggregation for
 202 all output quantities across all ensemble simulations was performed as follows:

- 203 1. Spatial aggregation: Averaging the country-wide 430 grid cells on a daily resolution, weighted by
 204 the share of arable land within each grid cell.
- 205 2. Temporal aggregation: Averaging or summing up from step 1 to obtain annual values; averages
 206 on a national scale were derived by dividing the totals by the total arable land area across all grids
 207 to obtain area-weighted average fluxes per hectare.



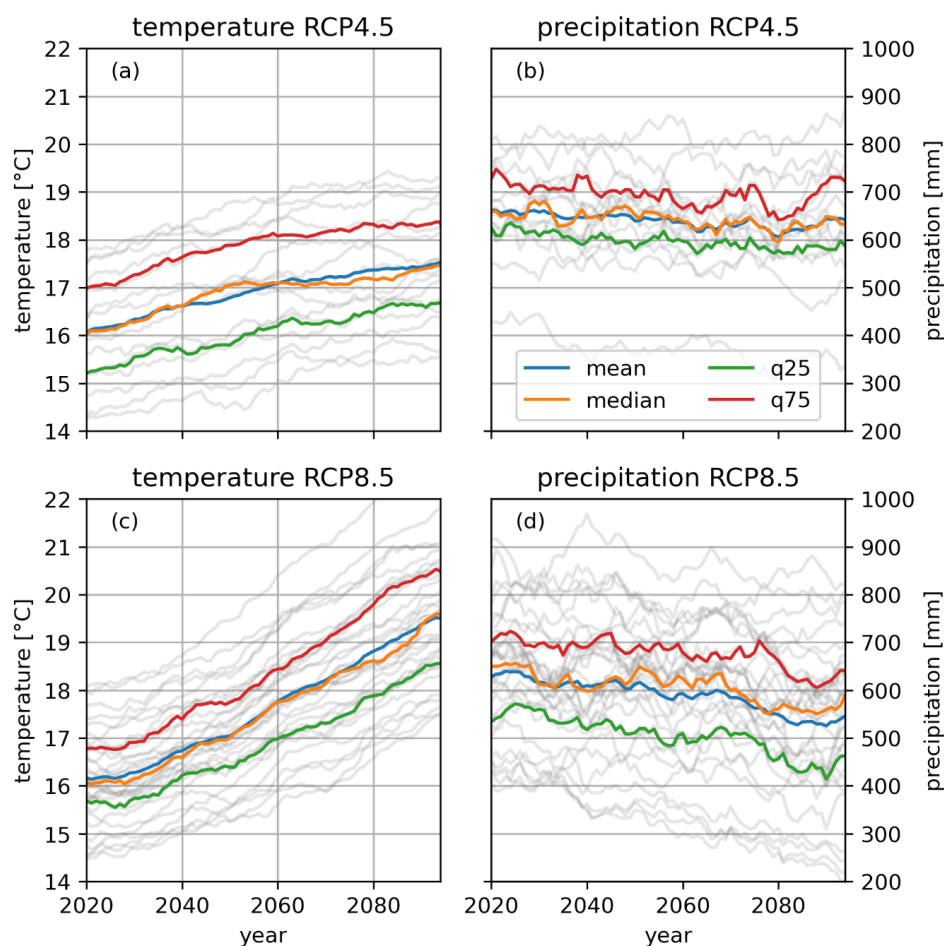
208 To assess the climate change impact, statistical analysis was applied across the ensemble time series from
 209 the above-mentioned aggregations, resulting in ensemble statistics such as means, medians, standard
 210 deviations, and 25- and 75-quartiles. Higher-level quantitative approaches, such as performing statistics
 211 on the grid cell basis, as done by Haas et al., (2022) was not considered in this study.

212 3 Results

213 Simulation of the Greek cropland production system under projected climate change conditions (starting
 214 1990, evaluation 2005-2100) displays distinct temporal and spatial patterns of impact on agricultural
 215 production, and carbon and nitrogen cycling dynamics in agricultural soils. The simulations account for
 216 increasing atmospheric CO₂ concentration under RCP4.5 and RCP8.5, and shifts in temperature and
 217 precipitation dynamics represented by the various regional climate model simulations.

218 3.1 Climate change characteristics of the EURO-CORDEX RCP4.5 and RCP8.5 ensembles

219 The climatic information provided by the EURO-CORDEX ensemble of simulations over the study region
 220 displays distinct spatio-temporal patterns of climate change, concerning temperature and precipitation.
 221 This information is subsequently used in the impact assessment of the LandscapeDNDC model.
 222 The analysis of the climate change prediction ensembles shows for the arable land in Greece, during the
 223 21st century, an average temperature increase of 1.37°C (increase in: ensemble median 1.35, Q25 of 1.43
 224 and Q75 of 1.31 °C) for RCP4.5, and of 3.21°C (increase in: ensemble median 3.30, Q25 of 2.74, Q75 of
 225 3.60°C) for RCP8.5. The standard deviations increase between present and future conditions, reflecting
 226 the increase in spread between the ensemble members. The data is shown on Figure 1 (a, c) and
 227 summarized in Table 2. For the precipitation dynamics, shown on Figure 1 (b, d), a systematic decrease is
 228 expected under both RCPs. More specifically, we see a decrease of 17.96 mm (change in: ensemble
 229 median -10.57, Q25 of -45.18, and Q75 of -9.74 mm) for RCP4.5 and a decrease of 102.52 mm (change in:
 230 ensemble median -91.05, Q25 of -120.16, and Q75 of -86.20mm) for RCP8.5. The standard deviations for
 231 the ensemble precipitation also rise, indicating a greater spread among the ensemble members. From the
 232 aforementioned analysis of the EURO-CORDEX ensemble, it becomes evident that the impact of climate
 233 change becomes more severe towards the end of the 21st century, and ensemble spread also increases
 234 moving away from the current period (towards the end of the 21st). Data is summarized in Table 2.
 235



236

237 Figure 1. Annual projections of temperatures (a, c), and precipitation (b, d) for arable land in Greece as
 238 10-year rolling means for RCP4.5 (a, b) and RCP8.5 (c, d). Data based on reprojected EURO-CORDEX
 239 ensembles considering only grid cells with arable land in Greece (see summary Table 2). Grey lines
 240 represent individual ensemble members, blue the mean, orange the median, and green and red the
 241 interquartile range.

242



243

244 Table 2. Temperature and precipitation analysis of the climate change ensembles for the present (2005-
245 2035) and future (2070-2100) conditions (30-year periods). Data based on reprojected EURO-CORDEX
246 ensembles (see Table 1) considering only grid cells with arable land in Greece.

	Temperature				Precipitation			
	Present	Future	Change rate		Present	Future	Change rate	
	[°C]	[°C]	[°C]	[%]	[mm]	[mm]	[mm]	[%]
RCP4.5								
Mean	16.05	17.42	1.37	8.5	661.62	643.66	-17.96	-2.7
Median	16.03	17.38	1.35	8.4	659.07	648.50	-10.57	-1.6
Std	1.27	1.37	0.10	7.9	91.08	121.79	30.71	33.7
Q25	15.21	16.64	1.43	9.4	625.25	580.07	-45.18	-7.2
Q75	16.99	18.30	1.31	7.7	728.42	718.68	-9.74	-1.3
RCP8.5								
Mean	16.17	19.38	3.21	19.9	627.86	525.34	-102.52	-16.3
Median	16.07	19.37	3.30	20.5	650.36	559.31	-91.05	-14.0
Std	0.97	1.31	0.34	35.1	129.19	158.50	29.31	22.7
Q25	15.69	18.43	2.74	17.5	534.01	413.85	-120.16	-22.5
Q75	16.79	20.39	3.60	21.4	701.94	615.74	-86.20	-12.3

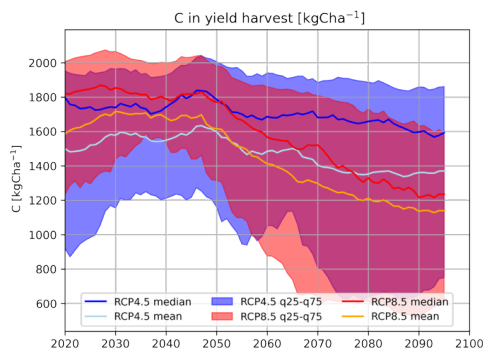
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248 3.2 Agricultural production response of major crops

249 The ensemble response to the climate change scenarios shows different responses for the SSP RCP4.5 and
250 RCP8.5, especially in the second half of the century, when assessing the averaged biomass carbon yield
251 across all various crops within the rotations for the various inventory simulations. Arable production
252 under RCP4.5 remains constant until 2045, followed by a clear decrease towards 2100 on average of 144
253 kg C ha⁻¹ yr⁻¹ (decline of approx. 9.5% compared to present conditions, while medians decrease by 111 kg
254 C ha⁻¹ yr⁻¹), while the spread of the ensemble simulations increases as well towards 2100, indicated by an
255 increase of the standard deviation. Under RCP8.5, arable production dynamics show similar behavior with
256 a much stronger decline after 2045, resulting in substantial yield reductions of 484 kg C ha⁻¹ yr⁻¹ (median
257 losses of 544 kg C ha⁻¹ yr⁻¹) corresponding to lower values of approx. 29% and 31% respectively, comparing
258 future to present conditions. Comparing predicted yields for the future time slice, the RCP4.5 scenario
259 shows significantly higher yields (corresponding to smaller losses) compared to the RCP8.5 ensemble.



260 Considering means, the RCP8.5 ensemble predicts 15% lower production, and even 24% lower yields
261 compared to the RCP4.5 ensemble (see the summary of future predicted arable production in Table 3).
262 For both scenarios, the IQR of the simulated yield ensembles increases from present to the future, for
263 RCP4.5 from 1080 to 1210 versus 612 to 975 kg C ha⁻¹ yr⁻¹ for RCP8.5, respectively, which can be seen in
264 Figure 2 and summarized in Table 3. The characteristics of the simulated production ensembles strongly
265 correlate with the ensemble dynamics for temperature and precipitation driving the simulations. Table 3
266 summarizes all results for the analysis of the simulation ensembles for straw removed from the fields after
267 the harvest.
268



269
270 Figure 2. Dynamics of averaged cropland production of the ensembles on the national scale under climate
271 change scenarios (analysis based on yearly area weighted averaged carbon yields across all crops on a
272 national scale).
273



274

275 Table 3. Analysis of arable production (crop yield and straw) of the simulation ensembles under climate
276 change scenarios (present: 2015 – 2034, future 2070 – 2099). Yield and straw are area weighted of all
277 crops across all 430 grid cells.

	arable production (yields)			straw harvest		
	[kg C ha ⁻¹ yr ⁻¹]			[kg C ha ⁻¹ yr ⁻¹]		
	Present	Future	Change rate	Present	Future	Change rate
RCP4.5						
Mean	1511.7	1367.7	-144.0	1082.2	995.6	-86.6
Median	1735.9	1624.6	-111.3	1114.8	1027.1	-87.7
Std	535.9	571.4	35.5	133.2	149.3	16.1
Q25	862.5	650.2	-212.3	1012.5	889.5	-123.0
Q75	1942.8	1860.6	-82.2	1175.2	1099.1	-76.1
RCP8.5						
Mean	1644.9	1161.1	-483.8	1108.4	865.7	-242.7
Median	1776.8	1233.1	-543.7	1142.0	862.1	-279.8
Std	471.9	511.2	39.3	161.7	186.3	24.6
Q25	1394.3	604.3	-790.0	1066.7	723.1	-343.6
Q75	2006.1	1578.9	-427.2	1199.2	1017.3	-181.9

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279 3.3 Full carbon and nitrogen balance

280 3.3.1 Carbon balance

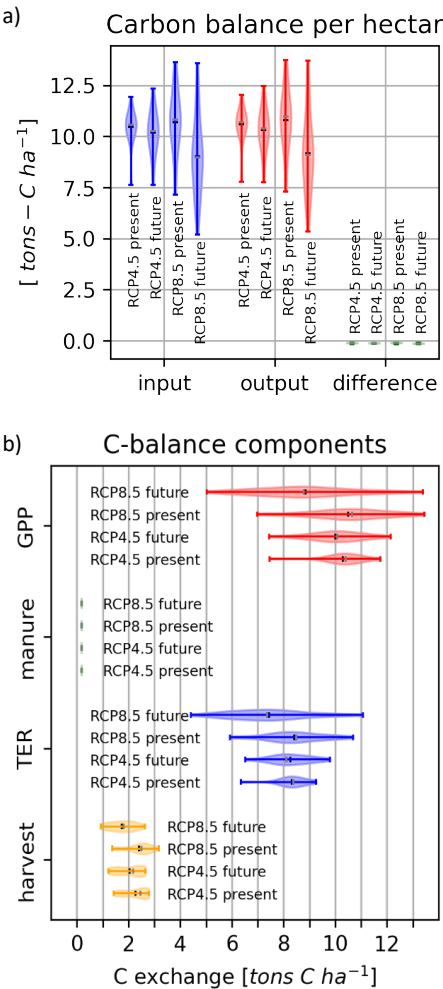
281 The ecosystem carbon balance consists of influxes, including GPP (gross primary production, or
282 photosynthesis), and carbon input via manure. The carbon outflux consists of TER (terrestrial ecosystem
283 respiration, encompassing both autotrophs and heterotrophs) and carbon removal via yield harvest. The
284 difference between these two represents the carbon gain or loss of the system. Figure 3 illustrates the
285 carbon fluxes for the different climate change scenarios, including the various carbon fluxes involved. The
286 net carbon flux of the system, i.e., a net carbon loss from the soil, is quantified in Table 3 for both present
287 and future conditions. At present, the RCP4.5 ensemble results in a yearly C loss of 122.1 or 264.9 kg C ha⁻¹



288 yr^{-1} , considering the mean versus median, respectively, and 120.6 or 168.1 $\text{kg C ha}^{-1} \text{yr}^{-1}$ losses for the
289 RCP8.5 ensemble, considering the mean versus median, respectively. For the future time slice, the RCP4.5
290 ensembles result in yearly C losses of 126.0 or 21.7 and 139.7 or 204.8 $\text{kg C ha}^{-1} \text{yr}^{-1}$, considering the mean
291 versus median for RCP4.5 versus RCP8.5 (see Table 4).
292 The partitioning of the carbon balance into different carbon fluxes is illustrated in Figure 3 b) and
293 summarized in Table 4. Overall, the impact of climate change on carbon balance displays non-significant
294 changes between the beginning and end of the 21st century in both RCP scenarios.



295



296 Figure 3. Carbon balance assessment of cropland cultivation in Greece on a national scale for a)
297 input/output/difference and b) the components of the Carbon Balance for RCP4.5 and RCP8.5 and time
298 slices present and future.

299



300

301 Table 4. Summary of the carbon balance for present and future conditions for a) RCP4.5 and b) RCP8.5
 302 scenarios. The C input via organic fertilization (manure) remains constant in the study and is therefore not
 303 listed.

	Present (2005-2035)			Future (2070-2100)			Change		
	[kg-C ha ⁻¹ yr ⁻¹]			[kg-C ha ⁻¹ yr ⁻¹]			[kg-C ha ⁻¹ yr ⁻¹]		
	Mean	Std	Median	Mean	Std	Median	Mean	Std	Median
RCP4.5									
GPP	10280.4	893	10395.9	10005.4	1119	10074.7	-275	226	-321.2
C in manure	175	0	175	175	0	175	0	0	0
TER	8313.3	657.8	8372.7	8265.2	811.8	8104	-48.1	153.9	-268.7
C-in-yield	2264.2	477.9	2463.1	2041.2	508.4	2167.4	-223	30.6	-295.7
ΔC flux	-122.1		-264.9	-126		-21.7	-3.9		243.2
RCP8.5									
GPP	10507.7	1540.9	10651.8	8855.2	1937.1	8781	-1652.4	396.2	-1870.8
C in manure	175	0	175	175	0	175	0		0
TER	8405.1	1119.5	8492.1	7428.7	1516.2	7358.5	-976.4	396.7	-1133.6
C-in-yield	2398.2	480.7	2502.8	1741.2	484.7	1802.3	-656.9	4	-700.4
ΔC flux	-120.6		-168.1	-139.7		-204.8	-19.1		-36.8

304

305 3.3.2 Nitrogen balance

306 The ensemble simulation uses nitrogen deposition as well as synthetic and organic nitrogen fertilization
 307 for the inventory simulations as input data. This data does not change between the climate change
 308 scenarios, and we, therefore, see in the ensemble results identical input fluxes for N deposition and N
 309 fertilization inputs. Nitrogen deposition from atmospheric sources contributed by 5.68 kg N ha⁻¹ yr⁻¹ on
 310 croplands (see Table 5 and Figure 5), while synthetic nitrogen fertilization was 100.88 kg N ha⁻¹ yr⁻¹ and
 311 organic nitrogen fertilization was 19.89 kg N ha⁻¹ yr⁻¹ across both scenarios and all years and rotations. In
 312 contrast, simulated biological nitrogen fixation accounted for 0.55 and 0.42 kg N ha⁻¹ yr⁻¹ for the present
 313 and future scenarios of RCP4.5, while in the RCP8.5 scenarios, the biological nitrogen fixation accounted
 314 for 0.49 and 0.27 kg N ha⁻¹ yr⁻¹ in the present and future conditions, respectively. (The crop management
 315 is based on the crop majority, such that legume crops only appear very rarely in the crop rotations, less
 316 than 2%.)

317 The gaseous out-fluxes that resulted from the ensemble simulations for present are N₂O emissions of
 318 0.494 or 0.476 kg N₂O–N ha⁻¹ yr⁻¹, NO emissions of 0.031 kg NO–N ha⁻¹ yr⁻¹, N₂ emissions of 4.806 or
 319 4.252 kg N₂–N ha⁻¹ yr⁻¹ and NH₃ emissions of 24.662 or 28.829 kg NH₃–N ha⁻¹ yr⁻¹ comparing ensemble



means versus medians in the case of RCP4.5 scenario. For the future time slice, we notice stronger differences in gaseous out-fluxes as N_2O emissions under RCP4.5 of 0.476 (mean and median) versus 0.453 or 0.457 $\text{kg N}_2\text{O-N ha}^{-1} \text{yr}^{-1}$ under RCP8.5. N_2 emissions show a decline in the future, comparing under RCP4.5 of 4.252 or 4.354 $\text{kg N}_2\text{-N ha}^{-1} \text{yr}^{-1}$ versus 3.377 or 3.171 $\text{kg N}_2\text{-N ha}^{-1} \text{yr}^{-1}$ under RCP8.5. Ammonia volatilization and out-fluxes show a strong future increase from 28.829 or 28.069 $\text{kg NH}_3\text{-N ha}^{-1} \text{yr}^{-1}$ to 35.040 or 34.205 $\text{kg NH}_3\text{-N ha}^{-1} \text{yr}^{-1}$, comparing ensemble means versus medians for RCP4.5 versus RCP8.5 climate change ensembles (compare Figure 4). Nitrate leaching is together with nitrogen removal via agricultural yields and straw the largest nitrogen flux within the system (see Figure 4). The ensemble simulations show an increase in nitrate leaching losses (comparing present to future time slices) for the mean from 54.304 to 56.049 $\text{kg NO}_3\text{-N ha}^{-1} \text{yr}^{-1}$ (from 50.083 to 51.421 for the median) for RCP4.5 and from 50.752 to 58.213 $\text{kg NO}_3\text{-N ha}^{-1} \text{yr}^{-1}$ (48.786 to 53.937 for the median) (see Figure 4). The analysis of the individual fluxes is illustrated in Figure 4.

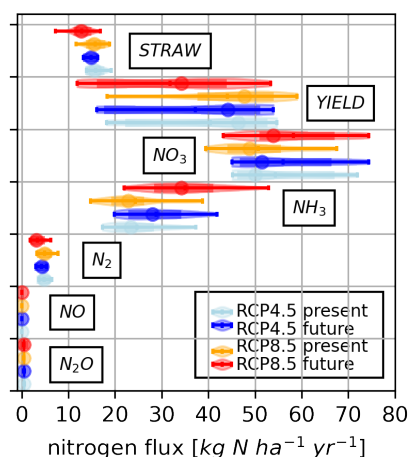
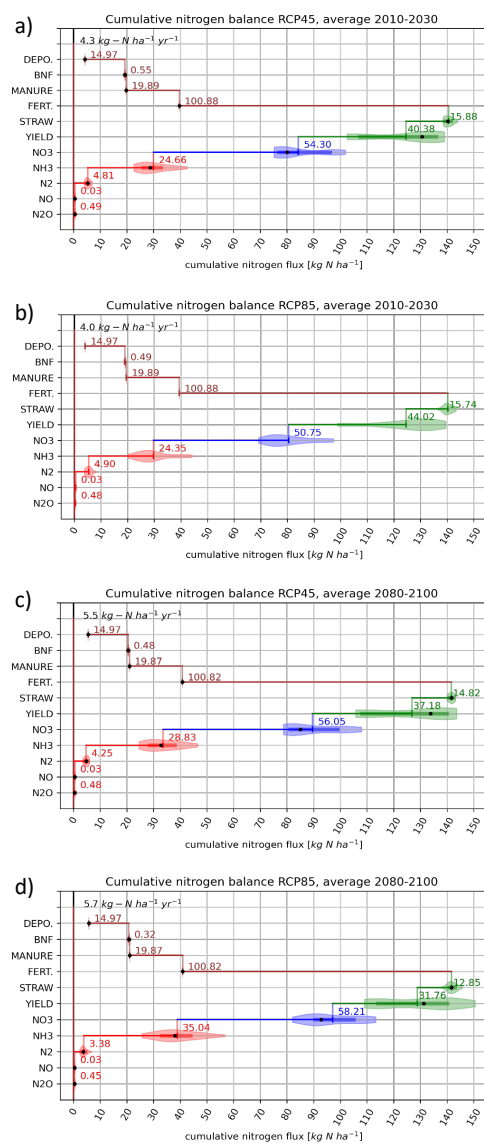


Figure 4. Violine / whisker diagram for all N outfluxes. The violin plots span the entire range; the whiskers (solid horizontal line) indicate the interquartile ranges from Q25 to Q75, while the vertical line indicates the median, and the point indicates the mean values.

Figure 5 illustrates the overall nitrogen balance (NB) in a waterfall diagram that cumulatively depicts all nitrogen out-fluxes starting with N_2O and the bottom and cumulating gaseous outfluxes in red, fluxes to open waters in blue, and N fluxes leaving the fields as yield/straw in green versus influxes (N-fertilization, manuring, BNF, and deposition) colored in brown. For each component in the NB, the associated uncertainty is illustrated as a violin representing the IQR. This diagram effectively conveys the overall soil nitrogen loss of the ensemble results as the difference between cumulative inflows and outflows. The net nitrogen loss for the period 2010-2030 results in 4.3 $\text{kg N ha}^{-1} \text{yr}^{-1}$ under RCP4.5, while it equals 4.0 kg N



345 $\text{ha}^{-1} \text{yr}^{-1}$ under RCP8.5, on a national scale. For the period 2070-2100, nitrogen loss is estimated to be 5.5
346 $\text{kg N ha}^{-1} \text{yr}^{-1}$ under RCP4.5 and 5.7 $\text{kg N ha}^{-1} \text{yr}^{-1}$ under RCP8.5.
347
348



349 Figure 5. Waterfall diagram depicting the climate change impact assessment of the nitrogen balance (NB)
350 of arable land cultivation for current (2010-2030) versus future (2080-2100) conditions under the RCP4.5
351 and RCP8.5 climate change scenarios. The violin plots span the entire range; the whiskers (solid horizontal
352 line) indicate the interquartile ranges from Q25 to Q75, while the vertical line indicates the median, and
353 the point indicates the mean values.

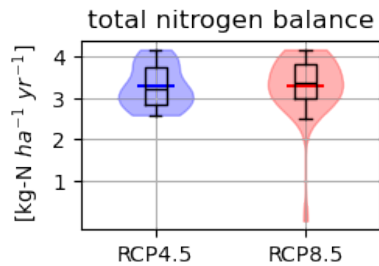


Figure 6. Distribution of the total N balances for the RCP4.5 and RCP8.5 for 2005 to 2100. Positive values indicate a net nitrogen outflux of the system. (violin plots with colored vertical bar as means, whisker plot with medians)

Table 5. Summary of the nitrogen fluxes for the present condition on a national scale and the projected rate of change, including prediction uncertainty.

Scenario	Present (2010-2030)			Future (2080-2100)			Change rate		
	[kg-N ha ⁻¹ yr ⁻¹]			[kg-N ha ⁻¹ yr ⁻¹]			[kg-N ha ⁻¹ yr ⁻¹]		
N fluxes	Mean	Std	Median	Mean	Std	Median	Mean	Std	Median
RCP4.5									
N ₂ O	0.494	0.033	0.498	0.476	0.037	0.476	-0.018	0.004	-0.022
NO	0.031	0.003	0.031	0.031	0.004	0.032	0.000	0.001	0.001
N ₂	4.806	0.824	4.784	4.252	0.710	4.354	-0.554	-0.114	-0.430
NH ₃	24.662	5.574	23.395	28.829	6.283	28.069	4.167	0.709	4.674
NO ₃	54.304	9.610	50.083	56.049	10.181	51.421	1.745	0.571	1.338
RCP8.5									
N ₂ O	0.479	0.027	0.480	0.453	0.037	0.457	-0.026	0.010	-0.023
NO	0.031	0.004	0.031	0.032	0.006	0.031	0.001	0.002	0.000
N ₂	4.898	1.079	4.894	3.377	1.013	3.171	-1.521	-0.066	-1.723
NH ₃	24.353	6.309	22.822	35.040	7.634	34.205	10.687	1.325	11.383
NO ₃	50.752	7.924	48.786	58.213	9.524	53.937	7.461	1.600	5.151



3.4 Climate impact on the carbon and nitrogen cycle

3.4.1 Long-term dynamics

Figure 7 shows the dynamics of the ensemble simulations for the soil carbon and soil nitrogen stocks of the 30 cm topsoil (illustrated as a 10-year rolling mean).

The dynamics of the SOC show from 2050 onwards a steady decrease in SOC/loss of soil carbon stocks by approx. $11.1 \text{ kg-C ha}^{-1} \text{ yr}^{-1}$ for RCP4.5 and $26.7 \text{ kg-C ha}^{-1} \text{ yr}^{-1}$ for RCP8.5, respectively, when considering the mean across the ensemble results (Figure 7 (a)). For the RCP8.5 ensemble results mean and the median show very similar behaviour, which means that the distribution of the ensemble results is close to symmetric. For the RCP4.5, the ensemble shows non-congruent and non-uniform dynamics of the median versus the mean, which means that the ensemble result distribution is not uniform but skewed towards higher values. The dynamics of the soil nitrogen stock behave uniformly with an 13.6 averaged carbon-to-nitrogen ratio.

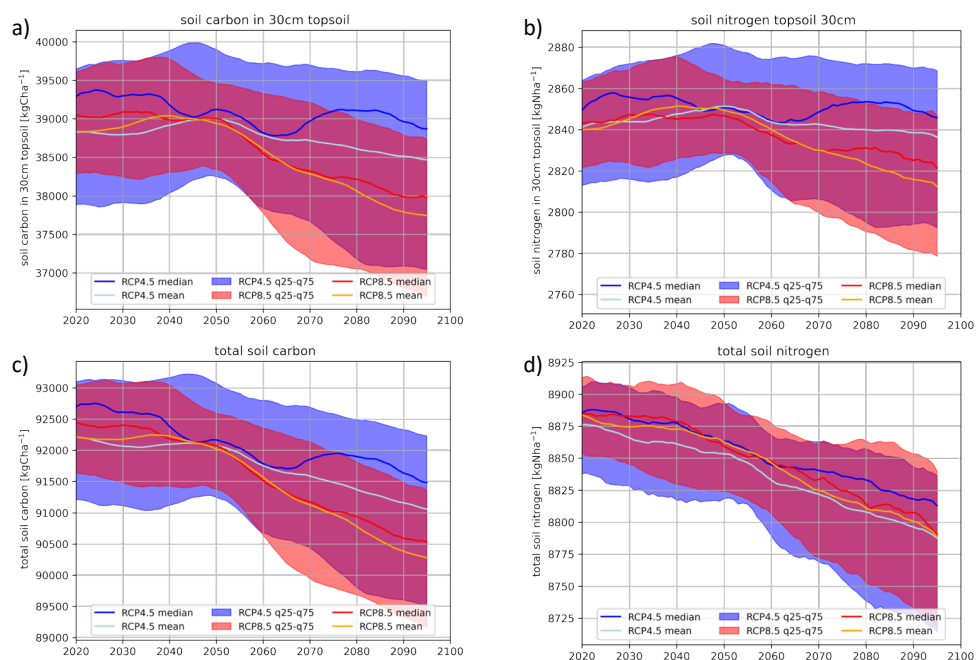


Figure 7. Dynamics of soil carbon (SC) and soil nitrogen (SN) for cropland cultivations in Greece: Dynamics of a) averaged carbon 30cm topsoil, c) total soil carbon stocks [kg-C ha^{-1}], b) averaged 30cm topsoil, and d) total soil nitrogen stocks [kg-N ha^{-1}].

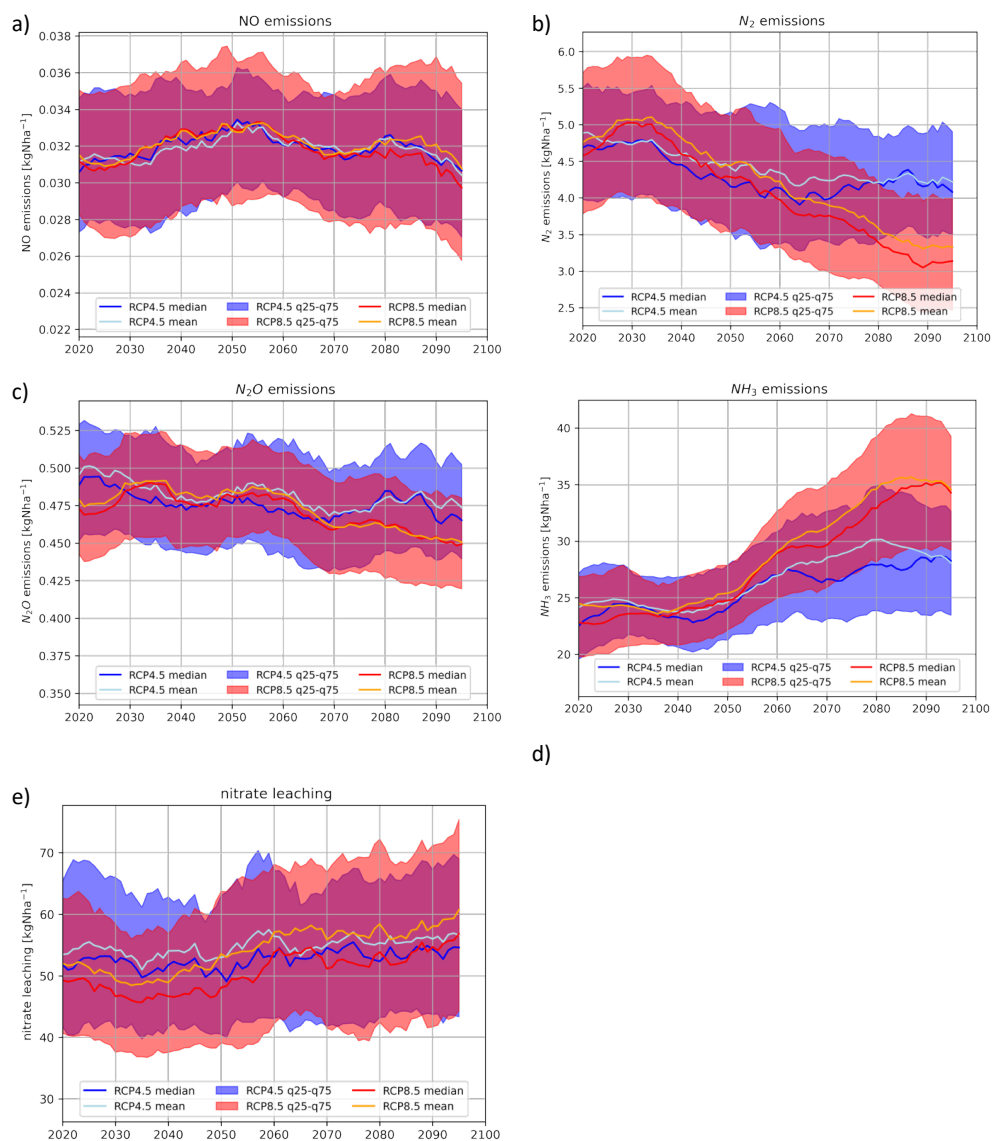
The dynamics of the gaseous and aquatic nitrogen fluxes are shown in Figure 8, a) to e). While the NO emissions are very low, they show uniform dynamics for both climate change scenarios. The N_2 emissions (from denitrification) show a rather uniform behaviour until 2060, when the ensembles of RCP4.5 deviate



383 from RCP8.5. The dynamics of the N_2O emissions of the ensembles behave quite uniformly, with
384 significantly deviating dynamics of the two climate change ensembles starting around 2075 and onwards.
385 For the ammonia emissions, the ensemble dynamics develop uniformly until around 2055, when the
386 warmer RCP8.5 ensemble results in higher emission strength of approx. $35 \text{ kg NH}_3\text{-N ha}^{-1} \text{ yr}^{-1}$ compared
387 to approx. $28 \text{ kg NH}_3\text{-H ha}^{-1} \text{ yr}^{-1}$ for RCP4.5 in 2095. The dynamics of the nitrate leaching show minor but
388 significant differences until 2050 and a uniform behaviour towards 2100 between the ensembles.



389



390 Figure 8. Temporal dynamics of gaseous and aquatic nitrogen fluxes (10-year rolling means) 2020 to 2095
 391 for a) NO emissions; b) N_2 emissions; c) N_2O emissions; d) NH_3 emissions, and e) nitrate leaching losses
 392 (all fluxes in $\text{kg-N ha}^{-1} \text{yr}^{-1}$).

393



394 4 Discussion

395 In this study, the combined carbon and nitrogen balance of cropland agriculture is assessed for the first
 396 time on a national scale. Until now, the published reporting and assessment of the full nitrogen balance
 397 in cropland and grassland systems have been scarce and limited to a regional scale. Despite the recognized
 398 importance of such reportings and analyses highlighted by leading scientists working on nitrogen cycling
 399 in soils (Grosz et al., 2023), only Schroeck et al. (2019) reported the N balance for two alpine catchments
 400 in Austria, Sifounakis et al. (2024) reported an uncertainty analysis for the N balance for a region in Greece
 401 and Rahimi et al. (2024) reported the full N balance for 6 catchments in Denmark.

402 Further, the concept of climate impact assessment of the C and N cycles in cropland ecosystems is
 403 introduced by propagating climate change model ensembles through an ecosystem model. It is
 404 highlighted that the large increase in temperatures within the climate change ensembles is expected to
 405 impact cropland productivity only marginally, assuming that irrigation water is still available, as it is under
 406 present conditions, and has been done in other studies (Deryng et al., 2011; Teixeira et al., 2013). We
 407 observe significant differences in our results for the present conditions in the ensemble results for RCP4.5
 408 and RCP8.5, despite these scenarios using the same historical climate conditions until 2005 and continuing
 409 with different climate projections due to varying global CO₂ emission scenarios towards 2100. Olschewski
 410 et al., (2024) have shown that the ensembles exhibit a significant spread for the historical time slice of the
 411 Mediterranean region and that bias correction of the individual ensemble representations enhances their
 412 predictive quality. Similar results have been observed in our study, as well as the spread in annual mean
 413 temperature and precipitation; for example, for the year 2000, this appears to be significant. In our study,
 414 the present conditions were defined as the mean values from 2005 to 2034 and are already within the
 415 projection time slice of the EURO-CORDEX RCPs. The major observed differences across ensembles in the
 416 current conditions are primarily driven by the variations in the selected climate change projection sets
 417 from the full EURO-CORDEX ensemble. We have decided to use all the available projections for RCP4.5
 418 and RCP8.5 to increase predictive quality into the future of the climate impact study. The selection of the
 419 sets of climate change projections used in this study was due to the availability of the datasets at the
 420 EURO-CORDEX data centers at the start of the study and their completeness to process input data for the
 421 model. The resulting mismatch was an outer constraint to the study, which we could not resolve, or rather
 422 had not anticipated at the start. We had only 14 climate data sets from common GCM/RCM combinations
 423 across the RCP4.5 and RCP8.5 scenarios, while the RCP4.5 ensemble contains 2 more datasets, and the
 424 RCP8.5 contains 18 climate datasets, unique to these scenarios.

425 The input dataset used in this study may impose some uncertainty on the results, as the fertilization rates
 426 may be underestimated. While the total synthetic and organic nitrogen fertilization will meet national
 427 statistics, the underlying size of arable land (used to calculate the fertilization rates) may be too large due
 428 to the former land use aggregation, including unfertilized orchards, vineyards, and fallow land as arable
 429 land.



430 The climate change impact on crop productivity under RCP4.5 reveals a very moderate decrease towards
 431 2100 in the simulation ensemble, while the IQR spread increases. This trend does not correlate with the
 432 annual temperature and precipitation trend shown and is likely resulting from, e.g., changes in seasonal
 433 precipitation distributions towards 2100 (data not shown). In the RCP8.5 ensembles, a statistically
 434 significant and severe decline in production starting in 2050 towards 2100 was observed, which correlates
 435 with trends of declining annual precipitation and an increase in the precipitation IQR spread of the
 436 ensemble, as seen in other studies (Bai et al., 2022; Carozzi et al., 2022; Deryng et al., 2011; Teixeira et
 437 al., 2013). Some of the climate projections under RCP8.5 reveal a decline in average annual precipitation
 438 from 500mm to 300mm, which will challenge agricultural production, and under such conditions, the
 439 irrigation management using approx. 150mm may be unrealistic.

440 The LandscapeDNDC model, as used in this study, provides a robust plant physiological process
 441 description, based on a temperature sum approach. Klicken oder tippen Sie hier, um Text einzugeben. In
 442 combination with water and nutrient limitation on daily growth, as well as water and heat stress, and
 443 plant senescence. The model is clearly limited by the challenges imposed by climate change, such as e.g.,
 444 anthesis heat stress causing severe losses for various grain crops, which may occur under RCP8.5 with a
 445 higher likelihood (Deryng et al., 2011; Olschewski et al., 2024; Sánchez-Benítez et al., 2022; Teixeira et al.,
 446 2013). On the other hand, LandscapeDNDC provides one of the most advanced soil bio-geochemical
 447 processes descriptions, proving a robust prediction of soil carbon and nitrogen cycling under present and
 448 future conditions (Basche et al., 2016; Grados et al., 2024; Jägermeyr et al., 2021; Petersen et al., 2021).
 449 Projecting current management practices into the future introduces another significant source of
 450 uncertainty; however, no alternative was available due to a lack of available management projections.

451 Winter vernalization will be under pressure as it is, e.g., for winter wheat under RCP8.5, as the number of
 452 chill days (vernalization) may decrease or even vanish by 2100, such that winter wheat cultivation may
 453 become impossible. Although LandscapeDNDC incorporates the vernalization process, its level of
 454 complexity may be insufficient to reliably estimate cereal production under extreme climate change
 455 conditions by the end of the century.

456 On the other hand, climate change may shift cultivation periods and phenology completely, towards
 457 winter, to avoid extreme heat stress or the introduction of multicropping seasons due to a prolongation
 458 of suitable climatic conditions (Bai et al., 2022; Petersen et al., 2021). This was not a focus of this study
 459 and has therefore not been investigated. The study has shown that under RCP8.5 with temperature
 460 increases and precipitation declines towards 2100, crop production will face major challenges, but will
 461 still be possible even under extreme conditions, and therefore, the management conditions used in this
 462 study remain within the possible trajectories.

463 The analysis of the soil carbon balance shows a decrease in carbon input into the system in the future due
 464 to climate change, while the respiration decreases accordingly. This reveals a very moderate loss of soil
 465 carbon starting in 2050 towards 2100, compared to (Basche et al., 2016; Carozzi et al., 2022). The loss



466 rates of 25 versus 30 kg C ha⁻¹ yr⁻¹ for topsoil (0-30cm) versus the total soil profile in the RCP8.5 are at the
 467 lower end of the published data and compare to the results of Haas et al. (2022) for the baseline scenarios.
 468 While Triantakostas et al. (2024) reported average loss rates of 1.5 t C ha⁻¹ yr⁻¹ for Greece over the
 469 past 10 years, Yigini & Panagos (2016) reported contrasting SOC increases using climate change scenarios
 470 until 2050. Lugato et al. (2014) modelled SOC dynamics until 2100 using two climate change realizations,
 471 deploying the Daycent model on LUCAS soil sampling points and upscaling to the EU-27. Our ensemble
 472 simulation results fit well with the SOC stocks for present conditions by Lugato et al. (2014), reporting, for
 473 the majority of Lucas points in Greece, topsoil C losses of similar ranges to those in our study, while some
 474 regions in Greece remain in equilibrium or achieve very small C gains until 2100. It is noticeable that the
 475 spread in simulated SOC content for the topsoil as well as the total soil profile increases towards 2100,
 476 which reflects the differences in C input (photosynthesis) and output (respiration due to decomposition)
 477 in some ensemble simulations, resulting in added uncertainty to the overall SOC estimation.
 478 On the national scale, the nitrogen outfluxes of the system are determined by the underlying management
 479 practices, and assuming a projection of this management into the future, it is clearly highlighted that for
 480 present conditions, the largest flux of nitrogen is the nitrate leaching into surface waters of approx 51 and
 481 54 kg NO₃-N ha⁻¹ yr⁻¹, which compares well with Sifounakis et al., (2024). This corresponds to 36 or 38 %
 482 of the nitrogen input into the system and poses a substantial threat to drinking water quality on the
 483 national scale. These findings are in line with recommendations by Karyotis et al., (2002), Velthof et al.,
 484 (2009) using the Miterra-Europe model or Lyra et al., (2021) reporting nitrate concentration observations
 485 in the Almyros basin under intense agricultural use. In our study, we neglected nitrate content in the
 486 irrigation water to avoid further uncertainty. We have used a static irrigation scheme by calendar
 487 day/phenology, which was projected into the future, not accounting for actual soil water content on
 488 irrigation day, irrigation water nitrogen load, and irrigation water availability due to climate change.
 489 The second largest nitrogen loss flux was ammonia volatilization to the atmosphere, driven by local
 490 conditions of slight to moderate alkalinity, with pH values of 7 and higher. The reported fluxes of 20% for
 491 present conditions, up to 30% under future conditions for alkaline soils, agree well with global estimates
 492 by Zhan et al. (2021) of 12 to 16% or Pan et al. (2016) of up to 18% of the applied fertilizers. These losses
 493 were found to increase in the future under climate change conditions due to their temperature
 494 dependence of the volatilization (Beaudor et al., 2025) supporting our findings. Shen et al., (2020)
 495 reported for U.S. cropland, that warming alone can raise agricultural NH₃ emissions by up to 80% by 2100,
 496 highlighting strong temperature sensitivities. These estimates indicate that the deposition scenarios used
 497 in this study, based on Haas et al., (2022) (derived from EMEP data), might underestimate the redeposition
 498 of ammonia into the landscape. The reported ammonia losses represent 17 to 18% of the total nitrogen
 499 outflux of the system.
 500 Analysing the N₂O emission fluxes, our study reports rather low N₂O emission fluxes compared to
 501 Sifounakis (2024), reporting N₂O emissions for the intensively cultivated region of Thessaly (Greece) of 2.6



502 kg N ha⁻¹ yr⁻¹ under much higher N influxes of up to 220 kg N ha⁻¹ yr⁻¹. N₂O emission measurements for
 503 Greece have not been reported in the literature. Carozzi et al. (2022) reported for European soils
 504 estimates of 1.2 kg N ha⁻¹ yr⁻¹ (STD of 0.2) and 1.57 kg N ha⁻¹ yr⁻¹ (STD 0.2) for the cases of RCP4.5 and
 505 RCP8.5, respectively, for the first half of the century. During the second half of the century, the estimation
 506 rose to 1.66 kg N ha⁻¹ yr⁻¹ (STD 0.3) and 1.93 kg N ha⁻¹ yr⁻¹ (STD 0.3) for the RCP4.5 and RCP8.5 scenarios,
 507 while our study reveals slightly declining emission strengths towards 2100.

508 The N₂O emissions in our study are lower when compared to the estimates of the latest Greek NIR
 509 (Hellenic Republic Ministry of Environment and Energy, 2025), reporting N₂O emissions from cropland
 510 soils of approx. 7.49 kt N₂O-N yr⁻¹ or 2.59 kg N₂O-N ha⁻¹ yr⁻¹.

511 Regarding the N₂ outflux, other model studies (e.g., Sifounakis, 2024, with LandscapeDNDC in Thessaly)
 512 show N₂ emissions of 15 kg N₂-N ha⁻¹ yr⁻¹ compared to approx. 4.5 kg N₂-N ha⁻¹ yr⁻¹ in our ensemble
 513 inventories for present conditions, which results from higher irrigation levels fostering denitrification
 514 upon N₂O emissions. Our ensemble study observed a stronger decline in N₂ versus N₂O emissions towards
 515 2100, which aligns with the decline in precipitation and, consequently, a decline in soil water and an
 516 increase in anaerobic soil conditions that hampers denitrification and N₂ emissions. We have not analyzed
 517 the dynamics of the N₂:N₂O relationships of each ensemble simulation.

518 The study underestimates the influence of legume crops as a nitrogen input source into the soil in Greece
 519 on a national scale, due to its consideration of only four major crops in arable management. The reported
 520 share of cultivated pulses in Greece is under 2% of the cropland area
 521 (ELSTAT: <https://www.statistics.gr/en/statistics/-/publication/SPG06/2023>, last access: February 2024),
 522 but (Sifounakis et al., 2024) has shown that the incorporation of legume crops as feed crops in crop
 523 rotations in one region in Greece has a large influence on the SOC dynamics and on the overall NB.

524 Comparing the simulated Nitrogen balances for the present and future conditions, a marginal increase in
 525 the yearly N deficit for the climate change ensembles is shown. Assuming an average C/N ratio of the soils
 526 at 11, these nitrogen losses are larger than the corresponding SOC losses, which indicates a higher loss of
 527 the soil nitrogen pools. The climate change impact on the NB is rather low when comparing future versus
 528 present conditions (change in approx. 0.2 and 1.2 kg N ha⁻¹ yr⁻¹ for RCP4.5 and RCP8.5, respectively).

529 The projected shifts in internal nitrogen fluxes are significant, with large declines in nitrogen harvest
 530 outfluxes towards increases in NH₃ volatilization and nitrate leaching losses in the future. While NH₃
 531 volatilization is temperature-driven, which impacts the equilibrium of NH₄ versus NH₃ due to Henry's law,
 532 a large portion will also be attributed to reduced nitrogen uptake, resulting in reduced productivity and
 533 more nutrients being available for physical excess pathways (volatilization/gas diffusion, and leaching).

534 It is highlighted that these results correspond to temporal and spatial averaging across the whole study
 535 region, and that spatio-temporal patterns have not been considered in the analysis. Furthermore, it is
 536 underlined that the ensemble results between RCP4.5 and RCP8.5 must be compared with caution, as
 537 each of these ensembles has been constructed with a different number and types of GCM/RCM



simulations, with the RCP8.5 scenario being significantly more populated compared to RCP4.5. At the beginning of the study, it was expected that a larger number of ensemble members would be beneficial and might increase the overall prediction quality. Our advice for future studies is to reduce uncertainty and always try to use sets of GCM/RCM projections across all analysed climate change scenarios. In that context, it is emphasized that the differences between the RCP scenarios are distinctively identified already for the present and near future conditions, when the underlying socioeconomic assumptions of each RCP start to influence. The EURO-CORDEX climate change ensembles claim to be bias-adjusted for the European conditions (ECMWF homepage), but large variations within the ensembles have been noticed for Greece, already for the historical period, which concludes that for such regions it is advised to perform local bias corrections as suggested by Olschewski et al. (2024). Menz (2023) has published bias-corrected EURO-CORDEX Data for 8 RCMs and is expected to have a reduced spread in the ensembles, while newer CMIP6 (Eyring et al., 2016) climate change projections are becoming available, with the split from historic to climate projection being closer to the present.

5 Conclusion

Ensembles of EURO-CORDEX climate change projections (RCP4.5 and RCP8.5) were propagated through the bio-geochemical process model LandscapedNDNC to assess the impacts on the carbon and nitrogen cycling and the associated GHG emissions from arable soils on a national scale for Greece. For the present time slice, the study presents for the first time a national-scale inventory of the full carbon and nitrogen balance of the Greek arable land cultivation from a process-based ecosystem model.

While the climate change ensembles show expected behaviour towards 2100 for Greece, such as a steady increase in surface temperature (median 1.35 °C for RCP4.5, 3.30°C for RCP8.5 over land), arable production will only decline substantially under RCP8.5 towards 2100, while predicted changes in precipitation are less recognisable.

The projected changes in the carbon and nitrogen balance, and their related excess outfluxes towards the end of the century, were relatively small. Despite pronounced annual warming, simulated soil carbon stocks remained stable, defying anticipated declines from temperature-driven mineralization.

The study outperforms the few previous climate impact assessments, which have mostly examined only one single flux, relied on a single climate projection, or reported results for individual sites rather than regional or national inventories.

To increase prediction reliability and reduce uncertainty, some aspects may have to be considered in future assessments:



- 570 a) The EURO-CORDEX ensembles for Greece show a large variance for the historic time span and
 571 therefore demonstrate the necessity of a general bias correction of the climate change
 572 predictions.
- 573 b) The use of identical GCM / RCM downscaled climate change projections in the ensembles for
 574 RCP4.5 and RCP8.5 is strongly advised for detailed climate change impact analysis to avoid the
 575 influence of additional model structural uncertainty only present in one of the scenarios.
- 576 c) Projections of irrigation management (spatial and temporal availability of irrigation water) need
 577 to be derived from individual climate change scenario results in advance of the simulations.
- 578 d) Climate change projections offer perspectives on the derivation of future crop cultivation
 579 strategies and timelines, such as shifts in crop calendars, double cropping potentials, and
 580 replacements of winter crops due to failing vernalization.
- 581 e) Nutrient supply and fertilization need to be dynamically calibrated/optimized towards the future
 582 to fulfill crop demands and respect soil nutrient availability.
- 583 f) The model lacks capabilities to simulate impacts of severe heat stress conditions (e.g., anthesis
 584 stress) and needs to be improved in this respect for climate change impact analysis.
- 585 g) Instead of improving the outdated input dataset (e.g., arable area aggregation), recent
 586 publications of high-resolution datasets for soil, climate, and arable management became
 587 available, leading to the ability of high-resolution/field-scale national inventory simulations.

588

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592

593 7 Data availability

594 All publication results (tables and data for figures) will be made available in the supplementary material
 595 associated with this paper.

596 8 References

597

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