REQUEST FOR A SPECIAL PROJECT 2024–2026

MEMBER STATE:	Spain
Principal Investigator[1]:	Etienne Tourigny
Affiliation:	Barcelona Supercomputing Center – Earth Sciences Department
Address:	Plaça Eusebi Güell, 1-3, 08034 Barcelona (Spain)
Other researchers:	BSC: Lina Teckentrup, Markus Donat, Raffaele Bernardello Uni Kassel: Florian Wimmer, Ruediger Schaldach
Project Title:	Exploring the potential contribution of Land-based mitigation technologies and practices (LMTs) for climate mitigation using the EC-Earth3-CC Earth System Model

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPESICCF**	
Starting year:	2025	
Would you accept support for 1 year only, if necessary?	YES x	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	120 M		
Accumulated data storage (total archive volume)[2]	[GB]	12,000		

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	0		
Total memory	[GB]	0		
Storage	[GB]	0		
Number of vGPUs[3]	[#]	0		

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

Principal Investigator: Etienne Tourigny

Project Title: Exploring the potential contribution of Land-based mitigation technologies and practices (LMTs) for climate mitigation using the EC-Earth3-CC Earth System Model

Extended abstract

I. Scientific plan

Negative emission solutions are expected to play a pivotal role in future climate actions and net zero emissions policy scenarios. To date most climate actions have focused on phasing out fossil fuels and reducing greenhouse gas emissions in, for example, industry, electricity, and transport. While zero emission trajectories in these sectors will remain a priority for decades to come, it is expected that residual GHG emissions will remain. To be able to fulfil the Paris Agreement and meet the world's climate goals, research, policy and markets are increasingly looking at negative emission solutions. Land-based mitigation technologies (LMTs) are expected to contribute significantly to the reduction of anthropogenic CO_2 emissions and storage of atmospheric CO_2 in a number of different reservoirs, in addition to the direct reduction of fossil fuel emissions. Examples of LMT include (i) Afforestation/Reforestation which increase the land CO_2 sink, (ii) bioenergy with and without Carbon Capture and Storage (BE/BECCS) which can replace fossil fuels and sequester some carbon in underground reservoirs, (iii) Reduced tillage which decreases the decomposition rates of Soil Organic Matter (SOM) and (iv) Agroforestry which can be used to increase the amount of forest cover when pasture and forest co-exist, thus increasing the land sink through forest growth.

In collaboration with UniKassel, the BSC Earth Sciences department has implemented a novel modelling framework combining the EC-Earth3-CC Earth System Model (ESM; Döscher et al., 2021) coupled to the LandSHIFT-G land-use model (Schaldach et al., 2011; Schüngel et al., 2022, Bringezu et al., 2021), as illustrated in Figure 1. LandSHIFT-G simulates sequences of land-use by integrating assumptions on the future development of the agricultural sector (e.g. crop/livestock production, changes in average crop yields) and assumptions on the implementation of a selection of LMTs as specified in global or regional scaling scenarios. Based on these land-use/land-cover changes (LUCC), EC-Earth3-CC simulates potential effects on regional climate, vegetation (both natural and managed) and atmospheric CO_2 concentrations, which has an indirect effect on global and regional climate. Changing potential crop yields due to climate change as modelled by the vegetation model LPJ-GUESS, a component of EC-Earth3-CC, are fed back to the land-use model, potentially affecting subsequent land-use patterns.

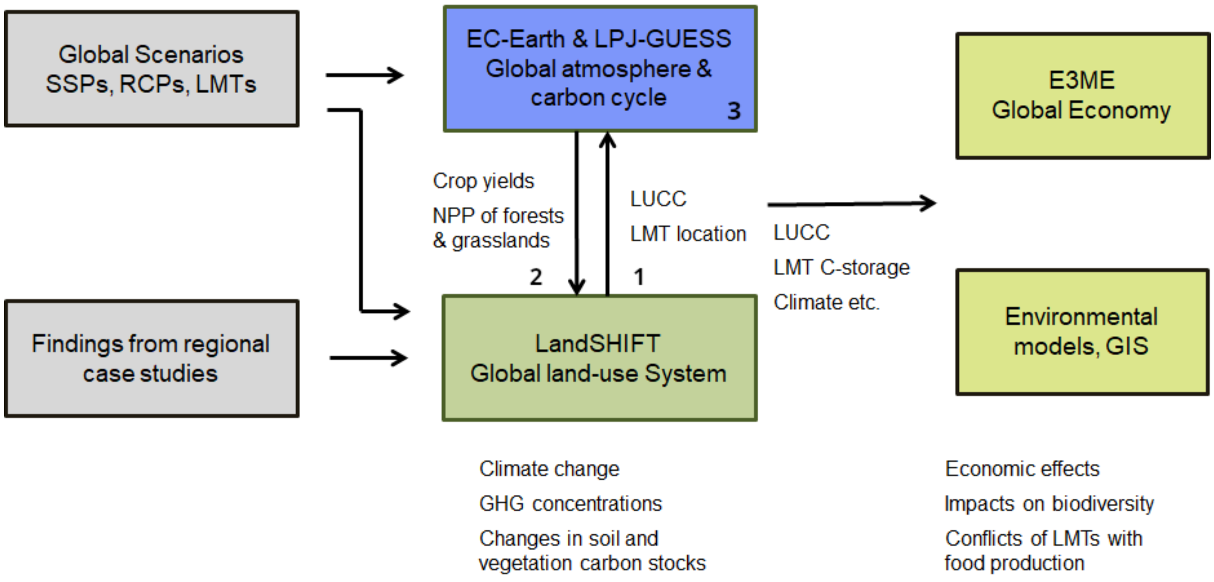

Figure 1: Diagram of the EC-Earth3-CC - LandSHIFT modelling framework.

EC-Earth3-CC is the carbon cycle version of the EC-Earth3 Earth System Model. The EC-Earth3-CC GCM (Global Climate Model) version 3.3 comprises of three major components:

- The atmospheric model IFS Cycle 36r4
- the ocean model NEMO 3.6 (Madec, 2015), which also includes the LIM3 sea-ice model (Rousset et al., 2015)
- OASIS3-MCT which couples all components

The carbon-cycle version of EC-Earth, EC-Earth3-CC includes additional components to represent the carbon cycle, also coupled via OASIS3-MCT:

- the LPJ-GUESS dynamic global vegetation model
- the PISCES ocean biogeochemistry model (Aumont et al., 2015)
- the EC-Earth CO2 box model

Figure 2 illustrates the components in the EC-Earth3-CC model, the exchanges among them as well as the coupling between LPJ-GUESS and LandSHIFT-G.

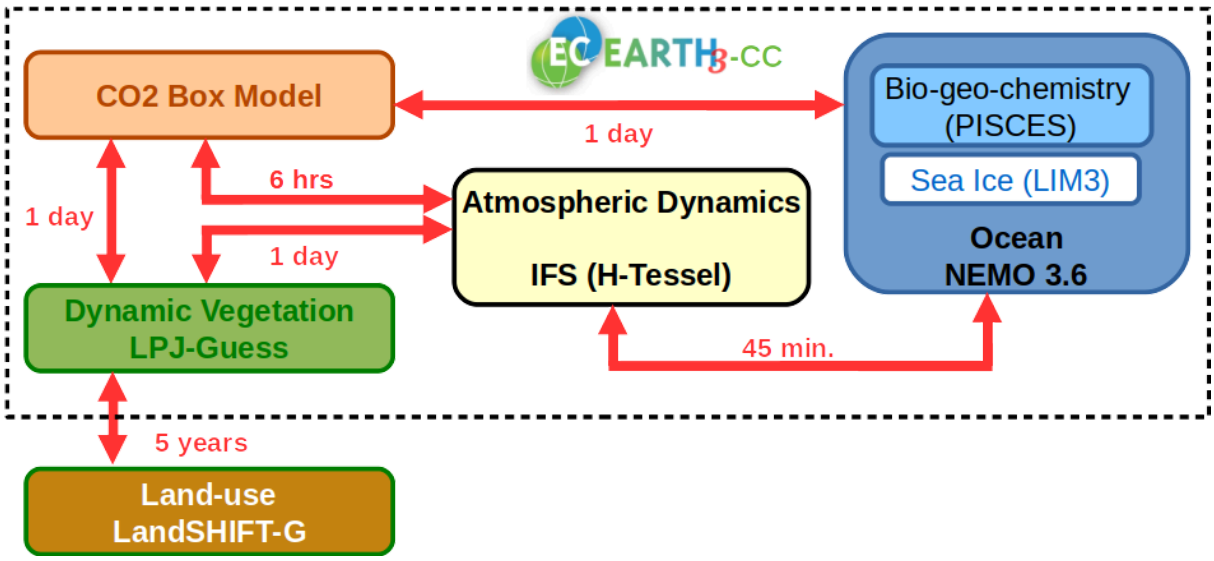

Figure 2: Components of the EC-Earth3-CC Earth System Model coupled to the LandSHIFT-G land-use model used in this study and the information exchange between them.

LPJ-GUESS is a widely used dynamic global vegetation model (DGVM) for global and regional climate-carbon studies (Lindeskog et al., 2013; Smith et al., 2014) and simulates the exchange of water, carbon and nitrogen by accounting for resource competition for light and space between plants. As a process-based second-generation DGVM, vegetation distribution, land use and land management are simulated dynamically. LPJ-GUESS is one of the first vegetation sub-models interactively coupled to an atmospheric model, in which the size, age structure, temporal dynamics, and spatial heterogeneity of the vegetated landscape are represented and simulated dynamically.

To simulate BECCS, we have implemented a new Crop Functional Type (CFT) in LPJ-GUESS which represents second-generation biofuels with a parametrization of the *Miscanthus gigantus* C4 perennial grass, based on the works of Krause (et al., 2020) and validated against in-situ measurements (Li et al., 2018). *Miscanthus gigantus* is known to have high yields and very good potential for biofuel production with and without CCS. We also implemented a system for storing captured carbon underground (BECCS) or in a biochar-like semi-permanent carbon storage. We have also implemented a simple representation of no-tillage which reduces SOM decomposition of certain crop patches. Finally a simple representation of Agroforestry was implemented in LandSHIFT-G and allows for forest to co-exist with pasture in the LPJ-GUESS land-use patterns.

We have designed three scenarios to study the mitigation potential of these LMT practises:

- “Reference” scenario following the SSP2-4.5 “baseline” scenario, in which land-use drivers are obtained from the IIASA database for the SSP2-4.5 scenario, but the actual land-use patterns are given by LandSHIFT-G with feedback from LPJ-GUESS.
- “High CDR Ambition” scenario, characterized by the coincidence of high ambitions to remove carbon dioxide from the atmosphere and strong regional engagement. There is a strong focus on the implementation of large-scale deployment LMTs, i.e. BECCS, aiming on the maximization of CDR. LMTs with relatively low CDR potential, e.g. agroforestry, are deployed at a rather low level, despite their co-benefits for other goals of sustainable development.
- “Moderate CDR Ambition” scenario, characterized by moderate ambitions to remove carbon dioxide from the atmosphere through measures taken in the land-use sector. Partly, this is because of moderate capacities due to a lack of regional engagement, which generally impedes the implementation of large-scale, international measures with high CDR potential (e.g. BECCS) and favours less technologically-demanding LMTs such as biofuels with biochar, agroforestry and soil conservation techniques.

II. Justification of the computing resources requested

We will perform a set of coupled climate model simulations using the three scenarios to evaluate the potential for CO_2 removal and climate mitigation of the different LMT portfolios, compared to the Reference scenario. In order to evaluate the robustness of the climate signal, we will perform a minimum of 5 ensemble members for each scenario. Simulations will be started from 2015 using the states from existing CMIP6 historical experiments performed by the BSC in the CMIP6 exercise, and finish in 2100 which is the end of the CMIP6 scenario period. Every 5 years, the LandSHIFT-G model will be run to compute the land-use transitions which will be used by LPJ-GUESS. We will perform a number of land-only simulations which have negligible computational cost, and an estimated 3 test runs for each scenario to ensure modelling setup produces reasonable results, and provide corrective measures if necessary. We thus will require resources to run 2,064 simulated years (3*86*8).

We will use the Autosubmit workflow manager (Manubens-Gil, et al., 2016) developed by the BSC Computational Earth Science (CES) group to submit the simulation, post-processing and cleanup jobs required for such a complex workflow. The Autosubmit workflow includes tasks to send processed model output to the BSC data storage and clean the HPC storage space within reasonable time limits byt processing raw model output and cleaning raw data as soon as possible. We will require a minimum of scratch space, consisting of model code, input files and temporary output files, to guarantee that we can run several experiments in parallel (each experiment consisting of a scenario and ensemble member occupying around 1,300 GB in tape storage consisting of model restarts, until the experiment is validated on our HPC). We will thus require a maximum of 12,000 GB tape storage which will be cleaned well before the end of the project.

Significant effort has been put into finding the optimal computing setup on the ECMWF hpc2020 supercomputer, using a modified oasis coupler optimization tool (lucia-lite) and employing machine files to ensure optimal load-balancing and minimizing the waste of computing resources. As a result of these optimizations, we identified the best configuration which requires 1408 cores (11 nodes), and the time taken to simulate a model year is approximately 2 hours, consuming on average 2800 CHPSY (Computing Hours Per Simulated Year).

The computing resources required to run the 2,064 simulated years (at a cost of 2800 CHPSY) amount to 5,779,200 CPU hours, or a total of 6,935,0400 CPU hours, when accounting for an extra 20% for some buffer for running the land-only runs, LandSHIFT-G and other post-processing work. Using the CPUH-to-SBU conversion factor of 17.06, we estimate a consumption of approximately 120,000,000 SBU (120 M SBU) on the ECMWF HPC2020 system.

III. Technical characteristics of the code to be used

IFS is an operational global meteorological forecasting model developed and maintained by the European Centre of Medium-Range Weather Forecasts (ECMWF). It also includes the H-TESSEL land surface model which manages surface water and energy fluxes using a tiling scheme. NEMO is a state-of-the-art modelling framework for the ocean used for oceanographic research, operational oceanography, seasonal forecasting and climate research studies. The global carbon cycle is then represented by (i) PISCES, which models ocean biogeochemistry, and (ii) LPJ-GUESS which simulates the evolution of the land vegetation, agricultural production and terrestrial carbon and nitrogen. IFS, PISCES and LPJ-GUESS are coupled to the EC-Earth CO2 box model to which tracks changes in atmospheric CO_2 concentrations from prescribed anthropogenic emissions and fluxes with ocean and vegetation (including the LMTs developed for LANDMARC), and thereby is able to capture feedbacks between all three realms. In this project we use the TL255-ORCA1 configuration, which corresponds to a spatial resolution of ≈ 80 km in the atmosphere/land and ≈ 100 km in the ocean.

IV. Relevant publications from the Special Project researchers

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégoz, M., Miller, P. A., Moreno-Chamarro, E., Nieradzik, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., and Zhang, Q.: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.

Bilbao, R., S. Wild, P. Ortega, J. Acosta-Navarro, T. Arsouze, P.-A. Bretonnière, L.-P. Caron, M. Castrillo, R. Cruz-García, I. Cvijanovic, F. J. Doblas-Reyes, M. Donat, E. Dutra, P. Echevarría,

A.-C. Ho, S. Loosveldt-Tomas, E. Moreno-Chamarro, N. Pérez-Zanon, A. Ramos, Y. Ruprich-Robert, V. Sicardi, E. Tourigny, J. Vegas-Regidor (2021), Assessment of a full-field initialized decadal climate prediction system with the CMIP6 version of EC-Earth, Earth Syst. Dynam., 12, 173–196, https://doi.org/10.5194/esd-12-173-2021

Hieronymus, J., M. Hieronymus, M. Gröger, J. Schwinger, R. Bernadello, E. Tourigny, V. Sicardi, I. Ruvalcaba Baroni, and K. Wyser (2024). Net primary production annual maxima in the North Atlantic projected to shift in the 21st century, Biogeosciences, 21, 2189–2206, doi:10.5194/bg-21-2189-2024.

Acosta, M. C., S. Palomas and E. Tourigny (2023). Balancing EC-Earth3 improving the performance of EC-Earth CMIP6 configurations by minimizing the coupling cost. Earth and Space Science, 10, e2023EA002912, doi:10.1029/2023EA002912.

Martín-Gómez, V., Y. Ruprich-Robert, R. Bernardello, E. Tourigny, M. Donat, P. Ortega and M. Samso Cabré (2023). Large spread in interannual variance of atmospheric CO2 concentration across CMIP6 Earth System Models. npj-Climate and atmospheric sciences, 6, doi:10.1038/s41612-023-00532-x.

Jones, C.D., J. E. Hickman, S.T. Rumbold, J. Walton, R.D. Lamboll, R. B. Skeie, S. Fiedler, P.M. Forster, J. Rogelj, M. Abe, M. Botzet, K. Calvin, C. Cassou, J.N.S. Cole, P. Davini, M. Deushi, M. Dix, J.C. Fyfe, N. P. Gillett, T. Ilyina, M. Kawamiya, M. Kelley, S. Kharin, T. Koshiro, H. Li, C. Mackallah, W.A. Müller, P. Nabat, T. van Noije, P. Nolan, R. Ohgaito, D. Olivié, N. Oshima, J. Parodi, T.J. Reerink, L. Ren, A. Romanou, R. Séférian, Y. Tang, C. Timmreck, J. Tjiputra, E. Tourigny, K. Tsigaridis, H. Wang, M. Wu, K. Wyser, S. Yang, Y. Yang and T. Ziehn (2021). The climate response to emissions reductions due to COVID‐19: Initial results from CovidMIP.

V. References

Aumont, O., Ethé, C., Tagliabue, A., Bopp, L., Gehlen, M. (2015). PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies. Geoscientific Model Development 8 (8), 2465–2513.

Bringezu S. et al. (2021) Environmental and socioeconomic footprints of the German bioeconomy. Nat Sustain 4, 775–783. https://doi.org/10.1038/s41893-021-00725-3.

Döscher, R., et al. .: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.

Madec, G. (2015). NEMO ocean engine. (chapter 3), France.

Krause A, Knoke T, Rammig A. A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management. GCB Bioenergy. 2020; 12: 346– 360. https://doi.org/10.1111/gcbb.12675 ..

Li, W., Ciais, P., Makowski, D. et al. A global yield dataset for major lignocellulosic bioenergy crops based on field measurements. Sci Data 5, 180169 (2018). https://doi.org/10.1038/sdata.2018.169 .

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., Smith, B. (2013). Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. Earth System Dynamics 4 (2), 385–407.

Manubens-Gil, D., Vegas-Regidor, J., Prodhomme, C., Mula-Valls, O., and Doblas-Reyes, F. J.: Seamless management of ensemble climate prediction experiments on hpc platforms, in: High Performance Computing & Simulation (HPCS), 2016 International Conference on, pp. 895–900, IEEE, 2016.

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., Benshila, R., Chanut, J., Levy, C., Masson, S., Vivier, F. (2015). The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities. Geoscientific Model Development 8 (10), 2991–3005.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D.M., Schüngel, J., Priess, J.A. (2011). An integrated approach to modelling land-use change on continental and global scales. Environmental Modelling & Software 26 (8), 1041–1051.

Schüngel, J., Stuch, B., Fohry, C., Schaldach, R. (2022). Effects of initialization of a global land-use model on simulated land change and loss of natural vegetation. Environmental Modelling & Software 148, 105287.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., Zaehle, S. (2014). Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. Biogeosciences 11 (7), 2027–2054.