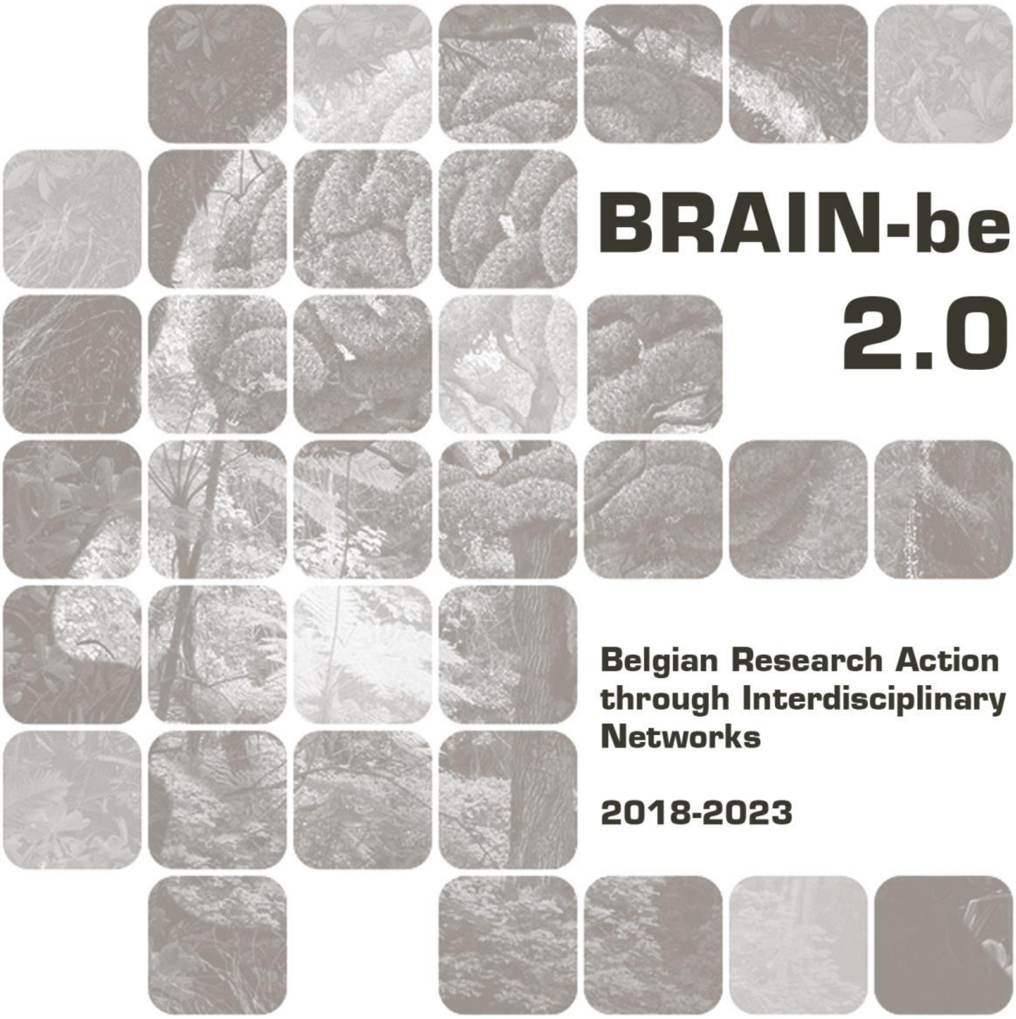

MAPPY-BE

Multisectoral Analysis of climate and land use change impacts on pollinators, plant diversity and crops yields.

Dr. Sarah Smet (University of Namur) – Pr. Nicolas Dendoncker (University of Namur)

Pillar 1: Challenges and knowledge of the living and non-living world

belspo .be

BRAIN-be 2.0

Belgian Research Action through Interdisciplinary Networks

2018-2023

NETWORK PROJECT

MAPPY-BE

Multisectoral analysis of climate and land use change impacts on pollinators, plant diversity and crop yields.

Contract - B2/181/P1/MAPPY-BE

FINAL REPORT

PROMOTORS:	PR. LOUIS FRANCOIS (University of Liège, Belgium)
	PR. NICOLAS DENDONCKER (University of Namur, Belgium)
	PR. KOOS BIESMEIJER (Naturalis Biodiversity Center, Netherlands)
	PR. HENS RUNHAAR (Utrecht University, Netherlands)
	DR. MERJA TÖLLE (University of Kassel, Germany)
	PR. THOMAS HICKLER (Senckenberg Gesellschaft für Naturforschung, Germany)
	DR. CHRISTOPH MÜLLER (Postdam Institute for Climate Impact Research, Germany)
	DR. LUCA TESTI (Consejo Superior de Investigaciones Cientificas, Spain)
	DR. ANDREAS MAYER (University of Natural Resources and Life Sciences, Austria)
AUTHORS:	DR. SMET SARAH (University of Namur, Belgium)
	PR. DENDONCKER NICOLAS (University of Namur, Belgium)

DATE: 06/10/2023

Published in 2023 by the Belgian Science Policy Office
WTCIII
Simon Bolivarlaan 30 bus 7
Boulevard Simon Bolivar 30 bte 7
B-1000 Brussels
Belgium
Tel: +32 (0)2 238 34 11
http://www.belspo.be
http://www.belspo.be/brain-be

Contact person: Aline van der Werf
Tel: +32 (0)2 238 36 71

SMET S., DENDONCKER N. ***Multisectoral analysis of climate and land use change impacts on pollinators, plant diversity and crop yields (MAPPY-BE)***. Final Report. Brussels: Belgian Science Policy Office 2023 – 20 p. (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))

TABLE OF CONTENTS

ABSTRACT

Context

Human activities influence the earth's systems to the extent that planetary boundaries for climate change, land-system change and biodiversity loss have already been crossed (Steffen et al., 2015, and references therein). These three global subsystems interact with complex feedback loops. Climate change affects agricultural practices, which in turn induce land use and land cover (LULC) change, e.g. increased deforestation for agricultural expansion leading to biodiversity losses. Agricultural intensification and expansion may in turn reinforce (local) climate change and affect pollinator communities (Senapathi et al., 2017). Climate change may also affect pollinators directly, through shifts in distribution, abundance or phenology and loss of essential crop pollinators negatively affects crop yield which may trigger more land use change. In addition, pollinators strongly depend on natural ecosystems, including forests with well-developed herb-rich understories (Hanula et al., 2015). The loss of plant diversity in forests is driven by LULC change, forestry management practices, agriculture and possibly climate change, strongly affects populations of (crop) pollinators and crop yield in turn (Garibaldi et al. 2013, 2016). The importance of and interaction between the various factors explaining pollinator decline, remains difficult to assess quantitatively in the absence of integrative models (Potts et al. 2016; Goulson et al., 2015). To safeguard healthy pollinator populations and crop pollination, a quantitative understanding of the complex interactions between climate, land use, ecosystem management, plant diversity and pollinators is needed.

Objectives

While no integrative framework exists yet to understand multi-crop/multi-sector interactions, MAPPY partners have made substantial progress recently: MASC (www.masc-project.be) produced high resolution insights in the interactions between climate and land use change across Belgium, while BELBEES (www.belbees.be/en) assessed impacts of land use and climate change on Benelux bumblebees (Marshall et al., 2018). To upscale this approach to the European continent, the next step was to develop several case studies across countries to test the models, which required a multidisciplinary transnational research network. This MAPPY collaborative project was an initiative in this direction. The overall objective of the MAPPY project was therefore to study quantitatively the processes linking pollinators, plant diversity and crop yields in the framework of climate and land use changes. Six case study regions were defined in the countries of the participating research teams: Eisenwurzen Nature Park (Austria), Wallonia (Belgium), River Rur catchment (Germany), Rhine-Main area (Germany), Zuid-Holland, Zeeland and Noord-Brabant Provinces (Netherlands), Cordoba Province in Andalusia (Spain).

Conclusions

The MAPPY project successfully coupled several models in order to evaluate the impacts of climate change and land use change on pollinators distribution. The climatic and vegetation models were calibrated and ran, at a high-resolution, for the six case studies regions which results will be also highly valuable for other applications. The land use change model was run for two regions as important socio-economic data were not available for some countries (esp. Germany and Spain; see mid-term report). Consequently, the subsequent developments and applications of the land use model focused on the Austrian and Belgian case study sites where all necessary data were fully available. The final socio-economic analysis was conducted for the Austrian case study where the partners evaluated 64 extreme scenarios in an option space approach. The main results are: (1) adverse climate change impacts in RCP 8.5 superimpose land-use change impacts on pollinators; (2) adapted land management can make a strong positive contribution to pollinator diversity, however climate change mitigation efforts are needed to keep this option for future action.

Keywords
Climate change; crop; forest; diversity; pollinators

1. INTRODUCTION

The response of agricultural yields to climate change has been repeatedly studied, but many important processes and interactions remain largely unexplored. One of these unexplored key processes is the linking of pollinators with climate and land use changes by controlling plant diversity and crop yields. Despite the recent achievements of the scientific community to provide deeper insight into the feedback processes and impacts associated with plant diversity and crop yields, there are still unaddressed scientific challenges that require a coordinated approach. In addition, the lack of sufficient direct interaction between researchers of diverse academic fields (such as biology and climatology) working closely together with stakeholders inhibits the efficient exploitation of fundamental research results to improve large-scale integrative modelling studies in a tangible way. Therefore, it is undeniable that there are potentially large societal benefits from a quantitative understanding of the complex Interactions between climate change, land use change, ecosystem management practices, plant diversity and pollinators.

We assembled a small set of complementary models to capture the dynamics of this complex system at regional level. First, we produced spatio-temporal high-resolution climatic scenarios over the studied regions, by using a regional climate model. Then, we used various crop models, dynamic vegetation models and species distribution models to assess the impacts of future climate change on agricultural yields and biodiversity, using ensemble means whenever relevant. An agent-based model was then used to derive detailed land use and land cover change scenarios for the future at the scale of the studied regions. This suite of models allowed to assess potential impacts on pollinator communities. Finally, the social and economic impacts of the projected changes in the studied regions were evaluated, by assessing quantitative indicators developed from the model results in concertation with project stakeholders.

The project was undertaken by a multidisciplinary research network, involving three traditionally separated scientific communities: (1) climate modellers producing climate scenarios, (2) climate impact modellers analysing the impacts of climate change on the environment and the ecosystems, and (3) human geographers or social scientists, simulating land use change and analysing climate change impacts on the society. This association would allow studying feedbacks which today remain largely unexplored. The affiliations of the partners are listed below.

Project coordinator:
Louis FRANÇOIS, Professor, University of Liège, Liège, Belgium
Project partners:
Partner 1: Nicolas Dendoncker, Professor, University of Namur, Namur, Belgium
Partner 2: Koos Biesmeijer, Professor, Naturalis Biodiversity Center, Leiden, Netherlands
Partner 2a: Hens Runhaar, Professor, Utrecht University, Utrecht, Netherlands
Partner 3: Merja Tölle, Dr, University of Kassel, Kassel, Germany
Partner 4: Thomas Hickler, Professor, Senckenberg, Frankfurt am Main, Germany
Partner 5: Christoph Müller, Dr, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
Partner 6: Luca Testi, Dr, Consejo Superior de Investigaciones Cientificas (CSIC), Cordoba, Spain
Partner 7: Andreas Mayer, Dr, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria

2. STATE OF THE ART AND OBJECTIVES

The MAPPY project aimed at improving our understanding of the complex dynamic between climate and land use change on the pollinators distribution, but as well aimed at enhancing current used models which were already at the highest state of the art.

Future regional climate changes were primarily studied with regional climate models (RCMs, Rummukainen et al., 2010). New model developments and computing power allows now limited-area convection-permitting climate simulations with less than 4 km horizontal resolution at longer time-scales (Kendon et al., 2014; Ban et al., 2014). The aim of the climate modelers was therefore to provide high horizontal resolution (~3 km) climate projections to the 2070 horizon over the six case study regions. These high-resolution climate scenarios were devoted to be used as inputs in a series of models analysing the impacts of climate and land use changes on the agricultural sector. The production of such high-resolution climate scenarios contributes to widening the range of the data already available, yet with higher resolution, which is useful for many applications.

Models of field crops suitable for evaluating climate change impacts on crop production are already available (e.g., DSSAT suite, Jones et al., 2003) although improvements are still required to improve simulations under extreme conditions which frequency is expected to increase (Pagani et al., 2017). In contrast with field crops, complete development, growth and yield models of most fruit crops have not been developed with some exceptions (e.g., OliveCan for olive trees, López-Bernal et al., 2018). Besides further developing tree crops in LPJmL (Fader et al., 2015) by the P6 team, MAPPY aimed to develop a tree crop model. The proposed model, that we is called TreeCan, would have the same skeleton as OliveCan in terms of phenology, water and carbon balances. Special attention was given to modelling frost damage, taking cold hardening into account (De Melo-Abreu et al., 2016). Transpiration was simulated using the model of Villalobos et al. (2013). We also used dynamic vegetation models (DVMs) and niche-based models (NBMs, also called species distribution models, SDMs) to assess the impacts of climate change and management practices on the selected forest regions and their biodiversity. DVMs simulated forest structure and productivity of both tree species and understorey, the latter being particularly relevant for pollinators. Changes in climate-driven disturbances, such as drought- and heat-related tree mortality (e.g., Steinkamp and Hickler, 2015) can also influence forest structure in this modelling framework. NBMs simulated selected important pollinated plants in forests, taking also changes in forest structure into account, e.g. the loss of light-demanding flowers if wood-harvest is lower than biomass increment or if forests are managed as even-aged monocultures with little structural variability. Changes in plant species range shifts are expected to potentially have profound effects on plant-pollinator networks (Schleuning et al., 2016). The aim of forestry and biodiversity modelers was therefore to investigate the impacts of climate change on forestry, and biodiversity using different types of vegetation and species distribution models in the case study regions. The results were used to obtain detailed estimates of future land use and land cover changes in these areas.

The agricultural land use was studied through the use of an agricultural land use change model in the form of an agent based model (ABM). ABMs allow the representation of the decision-making strategy of individual agents related to land use change by incorporating the complexity of the processes in a spatially explicit way, emergence and cross-scale dynamics of the topic (Bousquet &

Lepage, 2004). The model was driven by the yearly decisions made by individual farmers. In a fundamental way, agricultural land use change is mainly based on specific crop sequences (Leteinturier et al., 2006). However, in practice, decisions relative to agricultural land use changes and more widely to land use changes (e.g, conversion of agricultural land in residential areas) are also steered by a set of external factors. Among these, we find crop yields which in turn influence the choice of crop to sow next year, environmental rules and policies that sometimes require heavy investments and put new constraints on established farming techniques, increasing competition because of urbanisation pressure or economic reasons (phasing out of some of trade barriers by the CAP, decrease in subsidies from the CAP after 2020).

Based on all model results, pollinator modelers aimed at estimating impacts of climate and land use change on pollinator dynamics using a Species Distribution Model (SDMs). Species distribution models can identify potentially suitable habitats by linking species occurrences to environmental variables (Loyola et al., 2012; Silva et al., 2014). Although SDM is a common methodology in biogeography, the integration of biotic variables into the model is not often used (Giannini et al. 2013). Climate and land use can define the distribution of species, but they do so at different scales (Marshall et al. 2021).

In addition to the ecological dimension, changes in pollination also have large socio-economic implications. Since about 75% of all food crop species profiting from animal pollination (Klein et al., 2007), this ecosystem service is estimated to enhance global crop output by an additional US$ 235-577 billion annually (calculated on the basis of 2009 market prices and production, inflated to 2015 US$) (Potts et al., 2016). Khalifa et al. (2021) find, that 5-8% of all global crop production depend on pollination by bees and would be lost without it, and over 85% of wild flowering plants rely to some degree on pollination by animals. However, Bartholomée & Lavorel (2019) emphasized that the quantification of this ecosystem service is complicated, due to the coexistence of various indicators. They surveyed 131 papers and identified two main categories of pollination definitions relating to 1) the capacity of pollination and 2) the flow of pollination. The former is mostly determined by insect observations and captures, while the latter is determined by amount and quality of seeds/fruits (Bartholomée & Lavorel, 2019). Last, the project therefore aimed to assess social and economic impacts of the projected changes in the study regions. It also aimed to raise awareness and inform professionals for adaptation of their practices.

3. METHODOLOGY

To fulfil the objective of the project, seven models have been developed or calibrated and coupled. To that purpose, the project was subdivided in 6 work packages (WP). First, a climate model delivered climate projection from 1980 to 2070 according to two climate forcing scenarios (RCP 2.6 and RCP 8.5). The climate projections have been used as data input for three vegetation models aiming at simulating the future aerial carbon stocked into trees (LPJmL, von Bloh et al., 2018; Lutz et al., 2019; Herzfeld et al., 2021) and understory vegetation (CARAIB, Jacquemin et al., 2020). In addition, LPJ-guess was also used to project the future yields of a series of selected crops. The selected categories of crops pay heed to crops that are relevant to pollinators and to those that are economically significant across the research sites. This last property was important as the crop decision making process, within the land use agent-based model, was partially based on the economic profitability of the crops. The developed land use agent based model therefore used the future spatially-based crop yields projections as input to calculate the future crop profitability. The land use model, as a stochastic model, was ran between 20 and 40 times for each scenario and case study. The developed scenarios were based on various compliances to the Common Agricultural Policies regulations. The land use model outputs were used in addition to the forest and understory vegetation projections as input to a Species Distribution Model which aimed at modeling the dynamics of the pollinators. Species distribution models can identify potentially suitable habitats by linking species occurrences to environmental variables (Loyola et al., 2012; Silva et al., 2014). Finally, the last work package of the project aims to evaluate the socio-ecological and socio-economic impacts of scenario-dependent changes in the distribution of pollinators and the expected changes in crop yields and ecosystem services from forests in the six case study regions.

For an appropriate models coupling, a common spatial reference was built. First, the coordinates all the studied regions were unified and combined as an XYZ vector layer. Second, squared polygons were created considering an envelope of (0.0275°/2) for each coordinate. The output polygon vector layer is in the epsg:4326 WGS 84 projection system with polygons of 3 x 3 km size at the Equateur.
More detailed methodologies can be found in the description of the deliverables which are accessible on the MAPPY web site.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

The project was subdivided in 6 work packages (WP). We summarize below the main results for each WP. More detailed results can be found in the description of the deliverables which are accessible on the MAPPY web site.

WP1 provided transient high spatial resolution simulations at convection-permitting scale (3 km) for the future on several focal regions in Austria, Belgium, Germany, The Netherlands, and Spain. These future simulations, performed by partner 3, include climate change scenarios RCP2.6 and RCP8.5 up to 2070 time horizon. The model bias and its correction for impact models was addressed through applying a deterministic bias-correction method to the simulation outputs. The high-resolution climate simulation results were provided as bias-corrected and not-corrected data to all other WPs.

In WP2, various crop models were used to simulate crop yield response to the future climate scenarios established in WP1. The main crops existing or foreshadowed in the Spanish study site (Cordoba Province) were simulated in the team of partner 6 with various models. Fruit crops (almond, peach, grapewine) were simulated with FruitCan, a model specifically developed for this project, olive with OliveCan and annual crops (maize, sugar beet, wheat, sunflower, canola, faba beans and potato) with DSSAT 4.8. The crops from other study sites, in Austria, Belgium, Germany and The Netherlands, were simulated by the teams of partner 5 and the coordinator, with respectively the LPJmL and CARAIB models. LPJmL has been extended to include fruit trees (apple orchards) by Dr. Minoli at PIK (P6), however, due to the COVID pandemic work has been substantially delayed and the parameterization of the apple trees could not be finalized before the end of the project, when Dr. Minoli left academia. All other results for annual crops (wheat, maize, rapeseed, sugar beet and soybean) based on climate scenarios from WP1 could be supplied to partners in WP4. Yields of potato crops and grasslands, not simulated by LPJmL, were simulated with CARAIB and supplied to WP4. In general, the results of the different models indicate an increasing trend of the yields of many C3 crops with climate warming in the future (CO_2 fertilisation), but with a stronger interannual variability. Indeed, the simulated yields of several crops may reach very low values during dry years.

Within WP3, the newly developed forest management version of LPJ-GUESS (partner 4) was successfully applied to simulate the forests of the Central European study sites under two generalized future forest management scenarios (intensive forest management and no forest management). All simulated forests of the MAPPY study sites showed similar results, indicating that forests without any management exhibited denser forest canopy structures, resulting in reduced understorey vegetation as less light penetrates the forest canopy and reaches the forest floor. This reduction in understorey vegetation might negatively affect pollinators, as they prefer more open habitats with dense herbaceous understorey layers as habitat and food source. The CARAIB model (coordinator) was also used to simulate the evolution of the forests in the future. This model also generally forecasted denser forest canopies in the absence of management, but not on all sites. For instance, in the eastern part of the Ardenne (Wallonia, Belgium), substantial tree mortality (esp. spruce) was simulated in response to summer droughts in the future, which resulted in less dense tree canopies and increased understorey vegetation. Furthermore, the future distributions and productivities of a set of 30 understorey species (herbs and shrubs) which are used by pollinators were simulated by combining the results of CARAIB with those of a statistical distribution model.

In WP4 (partner 1), an existing agent-based model (ADAM) was upgraded and adapted, towards its application to the MAPPY case study sites. In this purpose, socio-economic data were collected for all sites in the first phase of the project, but difficulties to get some important data arose for some countries (esp. Germany and Spain; see mid-term report). Consequently, the subsequent developments and applications of the ADAM model focused on the Austrian and Belgian case study sites where all necessary data were fully available. ADAM was used to project future farm distribution (number and size) and agricultural land use (areal cover of main crops) until 2070 in both case study regions at 3 x 3 km resolution. The model used as inputs crop yields simulated in WP2 under the RCP2.6 and RCP8.5 climatic scenarios. These two climatic scenarios were combined with two economic scenarios specific to the land use model - Regional Communities (RC) and the Global Economy (GE) - making a total of 4 different scenarios. The model was run 40 times for each scenario in each region. The GE should favor bigger farms with less crop diversity while it would be the opposite for the RC scenario. Landscape diversity was assessed using the Shannon and Simpson indexes.

WP5 (partner 2) has developed large-scale climate-based and fine-scale land-use-based species distribution models for pollinators. Initial studies in the Netherlands delivered important knowledge on improving species distribution models using biotic interactions, land use and climate data. Then large-scale models and maps based on the climate data from WP1 were constructed for important wild bees and hoverflies in Central Europe. In addition to the pollinator presence maps, pollination index maps were produced for specific crops and their most important pollinators. Finally, fine-scale models and maps based on forest and land use data from WP3 and WP4 were then built at the regional scale. They show a strong effect on pollinator diversity with different land use and forest management scenarios in the case studies of Austria and Belgium. The maps developed in this work package provide important tools for future researchers from different fields.

WP6 was depending on results from the models from WP1 – WP5. Coupling all project outputs was very challenging. Thus partner 7, responsible for this work package, focused on the Austrian case study (Eisenwurzen), where scenario results from all WP's were combined, integrated, and complemented with 64 more extreme scenarios in an option space approach to understand the interactions between climate and land-use change and its effects on pollinator diversity. The results will be published in the Austrian Journal of Agricultural Economics and Rural Studies, a journal that is stakeholder related and targets readers outside of the scientific world. The main results are : (1) adverse climate change impacts in RCP 8.5 superimpose land-use change impacts on pollinators; (2) adapted land management can make a strong positive contribution to pollinator diversity, however climate change mitigation efforts are needed to keep this option for future action; (3) there are many hotspots with strong changes of pollinator diversity in the Northern parts of the Eisenwurzen, pollinator-adapted management can realize economic potential while at the same time respecting environmental conditions and the local cultural heritage.

5. DISSEMINATION AND VALORISATION

Dissemination of project results towards the **scientific community** has been made through presentations at scientific conferences and publications in scientific journals (see list of publications in the annex). Dissemination towards **stakeholders and end-users** of project results involves activities organized at the level of the whole consortium (by coordinator and its subcontractor ECORES) and more specific initiatives taken by individual partners in their countries.

Dissemination activities at the level of the whole consortium

Launching the project

- Development of a website, popularisation of content (https://www.mappy.uliege.be)
- Creation of a MAPPY logo and graphic image (+ templates for letters, ppt, reports, etc.)
- Production of an animated video explaining the dynamics of the MAPPY project
- Development of a survey addressed to stakeholders to encourage their involvement in the research and identify their recommendations in terms of disseminating the results. An online survey was spread, but the lack of results confirms the importance of direct meeting/discussions with stakeholders.

Communication with stakeholders

- 2 meetings have been organized in Belgium, and direct contacts were taken by partners
- Objectives: Stakeholders are experts able to consolidate our scenarios, and who might be interested in the results of the study for their practice. They are also potential prescribers of the results, able to spread our communication tool after the study.

Web and social media

- On the website: news and publications of the project; reporting for each work package
- Newsletters to stakeholders, to keep them informed of the evolution of the study.
- Social media (University of Liège, partners and stakeholders).

Final presentation and dissemination

- Newsletter / invitation and Final Event to present the results (ULiège – June 23rd – presential + distancial mode).
- Dissemination on the social media and web-agenda of the university and by partners.
- Dissemination of press kit including : press release, interview with Louis François, List of partners and funders, summary illustration (sketchnote).
- Communication pack (for stakeholders) including proposition of social media post and newsletter article (+ pressmap).

Specific initiatives by individual partners

- App rFrio developed by Spanish team with contributions of the University of Kassel's team (partner 7 & 4) – see Annex
- The project has led to intensified collaborations with the LPJ-GUESS community concerning European forest modelling (partner 5)
- Several exchanges with the municipality of Frankfurt-am-Main (partner 5)
- Several seminars were given at the University of Namur (partner 2) – see Annex
- Short newspaper article in an Austrian regional newspaper (partner 8)
- Oral presentation of the MAPPY project and preliminary results from WP6 at the Austrian Climate Day, an event that aims to bring together scientists, policy makers, NGO's and the interested wider society. The event was held in the Austrian case study region. (partner 8)
- Oral presentation of the project was accepted for at the conference of the Austrian Society of Agricultural Economics (ÖGA Tagung) in September 2023. (partner 8)
- Data and results from MAPPY for the Eisenwurzen region will be included in the European LTER RI network (https://elter-ri.eu/elter-plus/). (partner 8)

6. PUBLICATIONS

Ugolotti, A., Anders, T., Lanssens, B., Hickler, T., François, L., Tölle M. H., 2023. Impact of bias correction on climate change signals over central Europe and the Iberian Peninsula. *Front. Environ. Sci.*, 11. https://doi.org/10.3389/fenvs.2023.1116429

Moens, M., Biesmeijer, J. C., Klumpers, S. G. T., and Marshall, L., 2023. Are threatened species special? An assessment of Dutch bees in relation to land use and climate. *Ecology and Evolution*, 13, e10326. https://doi.org/10.1002/ece3.10326

Moens, M., Biesmeijer, J., Huang, E., Vereecken, N., and Marshall, L., 2022. The importance of biotic interactions in distribution models depends on the type of ecological relations, spatial scale and range. *Authorea Preprints*. November 07, 2022. DOI: 10.22541/au.166784603.30222525/v1

Minoli, S., Jägermeyr, J., Asseng, S., A., and Müller, C., 2022. Global crop yields can be lifted by timely adaptation of growing periods to climate change. *Nat Commun* **13**, 7079. *https://dx.doi.org/10.1038/s41467-022-34411-5*

Franke, J. A., Müller, C., Minoli, S., Elliott, J., Folberth, C., Gardner, C., Hank, T., Izaurralde, R. C., Jägermeyr, J., Jones, C. D., Liu, W., Olin, S., Pugh, T. A. M., Ruane, A. C., Stephens, H., Zabel, F., and Moyer, E. J. (2022). Agricultural breadbaskets shift poleward given adaptive farmer behavior under climate change. *Global Change Biology*, 28, 167–181. https://doi.org/10.1111/gcb.15868

von Jeetze, P.J., Weindl, I., Johnson, J.A., Borrelli, P., Panagos, P., Molina Bacca, E. J., Karstens, K., Humpenöder, F., Dietrich, J. P., Minoli, S., Müller, C., Lotze-Campen, H., and Popp, A., 2023. Projected landscape-scale repercussions of global action for climate and biodiversity protection. *Nat Commun* **14**, 2515 (2023). https://doi.org/10.1038/s41467-023-38043-1

Morales, A., and Villalobos, F.J., 2023. Using machine learning for crop yield prediction in the past or the future. *Frontiers in Plant Science*, 14, p.1128388

López-Bernal, Á., García-Tejera, O., Testi, L., and Villalobos, F.J., 2023. Modelling the impacts of cover crop management strategies on the water use, carbon exchange and yield of olive orchards. *Journal of Forestry Research,* 34(1), pp.283-295.

Mairech, H., López-Bernal, Á., Testi, L., and Villalobos, F.J., 2022. ClimaSG: A weather generator for crop modelling and water requirements studies. *Agricultural Water Management*, 271, p.107817.

Garcia-Tejera, O., Marcos-Matamoros, R., Basile, B., Mataffo, A., Scognamiglio, P., Prieto, H., Mancha, L., Cabral, I., Queiroz, J., Valente, J., and Alves, F., 2022. A method for using monthly average temperatures in phenology models for grapevine (Vitis vinifera L.). *Oeno One,* Nov. 2022.

Zhang, H., and Tölle, M. 2020. Evaluation of Agricultural Related Extreme Events in Hindcast COSMO-CLM Simulations over Central Europe. The 3rd International Electronic Conference on Atmospheric Sciences (ECAS 2020), 16–30 November 2020; *Sciforum Electronic Conference Series*, Vol. 3, 2020

Presentations at scientific conferences

François, L. ,Ronsmans, M. ,Lanssens, B.,Verma, A. ,Smet, S., Dendoncker, N., Moens, M., Biesmeijer, K. ,Runhaar, H., Tölle, M. , Ugolotti, A., Anders, T., Hickler, T., Müller, C., Minoli, S. , Testi, L., Garcia, O. , Villalobos, F., ,Mayer, A., Egger, C.: The MAPPY study: a multi-sectoral analysis. 6th European Climate Change Adaptation Conference 2023, Dublin, Ireland, 19-21 June 2023.

Lanssens, B., François, L., Hambuckers, A., Moens, M., Anders, T., Tölle, M., Verma, A., and Remy, L.: What future for pollinators in the understorey vegetation under the impact of climate change ? EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023, EGU23-13210, https://doi.org/10.5194/egusphere-egu23-13210, 2023.

Verma, A., Francois, L., Jacquemin, I., Lanssens, B., Hambuckers, A., Ugolotti, A., Tölle, M., and Hallot, E.: Reducing uncertainty in extreme weather vegetation stress modeling using satellite-model approach at high resolution, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-15565, https://doi.org/10.5194/egusphere-egu23-15565, 2023.

Lanssens, B., François, L., Hambuckers, A., Moens, M., Anders, T., Tölle, M., Verma, A., and Remy, L.: Assessing the effects of climate and land use changes on the distribution and growth of important plants species for pollinators. EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-4559, https://doi.org/10.5194/egusphere-egu22-4559, 2022.

Verma, A., Francois, L., Jacquemin, I., Lanssens, B., Tölle, M., Matej, S., and Egger, C.: Sensitivity analysis of terrestrial carbon budget with changing land use land cover and climate by combining dynamic vegetation model and satellite observed data at high resolution over Austria- Eisenwurzen, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6506, https://doi.org/10.5194/egusphere-egu22-6506, 2022.

Ugolotti, A. and Tölle, M.: Impact of statistical bias correction on the climate change signal of extreme climate indices from convection-permitting climate simulations over central Europe, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-372, https://doi.org/10.5194/egusphere-egu22-372, 2022.

Tölle, M. and Churiulin, E.: The role of different land cover input data on local climate and its extremes, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6507, https://doi.org/10.5194/egusphere-egu22-6507, 2022.

Lanssens, B., François, L., Hambuckers, A., Moens, M., Anders, T., Tölle, M., and Remy, L.: Impact of climate change on the distribution and diversity of vegetation species important for pollination. Changements globaux et gestion de la transition : au singulier ou au pluriel ? Colloque U. R. SPHERES, Université de Liège, Liège, Belgium, 20-21 October 2022. https://hdl.handle.net/2268/302624

Ugolotti, A.: Projections of climate extremes under RCP-8.5 scenario for central Europe. COSMO-CLM Assembly 2022, 19-23 September 2022.

Zhang, H. and Tölle, M.: Evaluation of agricultural-related extreme events in hindcast COSMO-CLM simulations over Central Europe, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-9507, https://doi.org/10.5194/egusphere-egu21-9507, 2021.

Zhang, H., and Tölle, M.: Evaluation of Agricultural Related Extreme Events in Hindcast COSMO-CLM Simulations over Central Europe. Presentation at the 3rd International Electronic Conference on Atmospheric Sciences (ECAS 2020), 16–30 November 2020.

Zhang, H. and Tölle, M.: Evaluation of hindcast COSMO-CLM simulation over Central Europe and Spain, COSMO-CLM Assembly 2020.

7. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of BELSPO.
We also would like to acknowledge the input from the team of researchers from the University of Natural Resources and Life Sciences (Vienna, Austria), funded by the Federal Ministry of Austria and Austrian Research Promotion Agency, for their valuable input in the definition of local parameters that were necessary for the land use model applied to the Austrian case study. Finally, we thank every members of seven team of researchers involved in this project.

8. BIBLIOGRAPHY

Ban, N., Schmidli, J. and Schär, C., 2014. Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. *J. Geophys. Res. Atmos.* 119, 889–7907, doi:10.1002/2014JD021478

Bartholomée, O., & Lavorel, S. (2019). Disentangling the diversity of definitions for the pollination ecosystem service and associated estimation methods. *Ecological Indicators*, *107*, 105576. https://doi.org/10.1016/j.ecolind.2019.105576

Beckers, V., Beckers, J., Vanmaercke, M., Van Hecke, E., Van Rompaey, A., and Dendoncker, N. 2018. Modelling farm growth and its impact on agricultural land use: a country scale application of an agent-based model. Land, 7, 109.

Bousquet F. and Le Page, C., 2004. Multi-agent simulations and ecosystem management: review. *Ecol. Model.* 176, 313-332.

De Melo-Abreu J.P., Villalobos F.J. and Mateos, L., 2016. Frost Protection. In: Villalobos F., Fereres E. (eds). Principles of Agronomy for Sustainable Agriculture. Springer.

Fader, M., von Bloh, W., Shi, S., Bondeau, A., Cramer, W. 2015. Modelling Mediterranean agro-ecosystems by including agricultural trees in the LPJmL model. *Geosci. Model Dev.* 8, 3545-3561, doi: 10.5194/gmd-8-3545-2015.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., et al., 2013. Wild pollinators enhance fruit set of crops regardless of honey-bee abundance. *Science* 339, 1608-1611.

Garibaldi, L.A., Carvalheiro, L.G., Vaissière, B.E., Gemmill-Herren, B., Hipólito, J., Freitas, B.M., Ngo, H.T., et al., 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science* 351, 338-391.

Giannini, T. C., Chapman, D. S., Saraiva, A. M., Alves-dos-Santos, I., & Biesmeijer, J. C. (2013). Improving species distribution models using biotic interactions: a case study of parasites, pollinators and plants. Ecography, 36(6), 649-656.

Goulson, D., Nicholis, E., Botias, C. and Rotheray, E.L., 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347(6229), doi: 10.1126/science.1255957.

Hanula, J.L., Horn, S. and O'Brien, J.J, 2015. Have changing forests conditions contributed to pollinator decline in the southeastern United States? *Forest Ecol. Manage.* 348, 142-152.

Herzfeld, T., Heinke, J., Rolinski, S., Müller, C., 2021. Soil organic carbon dynamics from agricultural management practices under climate change. Earth Syst. Dynam. 12, 1037-1055.

Jacquemin, I., Dury, M., Henrot, A.-J., Beckers, V., Berckmans, J., Dendoncker, N., Hamdi, R., Hambuckers, A., Tychon, B., Francois, L., 2020. High-resolution simulations of natural and agricultural ecosystems over Belgium with the CARAIB Dynamic Vegetation Model. Geo-Eco-Trop 44(4):541-552

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. and Ritchie, J.T., 2003. DSSAT Cropping System Model. *Eur. J. Agron.* 18, 235-265.

Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C. and Senior, C.A., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Chang.* 4(7), 570-576.

Khalifa, S. A. M., Elshafiey, E. H., Shetaia, A. A., El-Wahed, A. A. A., Algethami, A. F., Musharraf, S. G., AlAjmi, M. F., Zhao, C., Masry, S. H. D., Abdel-Daim, M. M., Halabi, M. F., Kai, G., Al Naggar, Y., Bishr, M., Diab, M. A. M., & El-Seedi, H. R. (2021). Overview of Bee Pollination and Its Economic Value for Crop Production. *Insects*, *12*(8), 688. https://doi.org/10.3390/insects12080688

Kleijn, D., Kleijn, Winfree, R., Bartomeus, I., Carvalheiro, L. G., Henry, M., Isaacs, R., Klein, A. M., Kremen, C., M'Gonigle, L. K., Rader, R., et al., 2015). Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nat. Commun.* 6, 7414, doi:10.1038/ncomms8414.

Leteinturier, B., Herman, J. L., De Longueville, F., Quintin, L. and Oger, R., 2006. Adaptation of a crop sequence indicator based on a land parcel management system. *Agric. Ecosyst. Environ.* 112(4): 324-334.

López-Bernal, A., Morales, A., García-Tejera, O., Testi, L., Orgaz, F., De Melo-Abreu, J.P. and Villalobos, F.J., 2018. OliveCan: a process-based model of development, growth and yield of olive orchards. *Front. Plant Sci*. 9, 632, https://doi.org/10.3389/fpls.2018.00632.

Loyola, R. D., Lemes, P., Faleiro, F. V., Trindade-Filho, J., & Machado, R. B. (2012). Severe loss of suitable climatic conditions for marsupial species in Brazil: challenges and opportunities for conservation. PloS one, 7(9), e46257.

Lutz, F., Herzfeld, T., Heinke, J., Rolinski, S., Schaphoff, S., von Bloh, W., Stoorvogel, J.J., Müller, C., 2019. Simulating the effect of tillage practices with the global ecosystem model LPJmL (version 5.0-tillage). Geosci. Model Dev. 12, 2419-2440.

Marshall, L., Biesmeijer, J.C., Rasmont, P., Vereecken, N., Dvorak, L., Fitzpatrick, U., Francis, F., Neumayer, J., Ødegaard, F., Paukkunen, J.P.T., Pawlikowski, T., Reemer, M., Roberts, S.P.M., Straka, J., Vray, S. and Dendoncker, N., 2018. The interplay of climate and land use change affects the distribution of EU bumblebees. *Glob. Chang. Biol.* 24, 101-106.

Pagani, V., Guarneri, T., Fumagalli, D., Movedi, E., Testi, L., Klein, T., Calanca, P., Villalobos, F.J., López-Bernal, A., Niemeyer, S., Bellocchi, G. and Confalonieri, R., 2017. Improving cereal yield forecasts in Europe – The impact of weather extremes. *Eur. J. Agron.* 89, 97-106.

Potts, S. G., V. Imperatriz-Fonseca, H. T. Ngo, M. A. Aizen, J. C. Biesmeijer, T. D. Breeze, L. V. Dicks, L. A. Garibaldi, R. Hill, J. Settele and A. J. Vanbergen, 2016. Safeguarding pollinators and their values to human well-being. Nature 540(7632), 220-229.

Rummukainen, M., 2010. State-of-the-art with regional climate models. *WIREs Clim. Chang.* 1, 82-96, doi:10.1002/wcc.8.

Schleuning, M., Fründ, J., Schweiger, O., Welk, E., Albrecht, J., Albrecht, M., Beil, M., Benadi, G., Blüthgen, N., Bruelheide, H., et al., 2016. Ecological networks are more sensitive to plant than to animal extinction under climate change. *Nat. Commun*. 7, 13965, oi: 10.1038/ncomms13965.

Senapathi, D., Goddard, M.A, Kunin, W.E. and Baldock, K.C.R., 2017. Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. *Funct. Ecol.* 31, 26–37.

Silva, D. P., Gonzalez, V. H., Melo, G. A., Lucia, M., Alvarez, L. J., & De Marco Jr, P. (2014). Seeking the flowers for the bees: integrating biotic interactions into niche models to assess the distribution of the exotic bee species Lithurgus huberi in South America. Ecological Modelling, 273, 200-209.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., ersson, L.M., Ramanathan, V., Reyers, B. and Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223), 1259855–1259855.

Steinkamp, J. and Hickler, T., 2015. Is drought-induced forest dieback globally increasing? . *Ecol.* 103(1), 31-43, doi: 10.1111/1365-2745.12335.

Villalobos, F.J., Testi, L., Orgaz, F., García-Tejera, O., López-Bernal, A., Gonzalez-Dugo, M.V., Ballester-Lurbe, C., Castel, J.R., Alarcon-Caballero, J.J., Nicolas-Nicolas, E., Girona, J., Marsal, J. and Fereres, E., 2013. Modelling canopyconductance and transpiration of fruit trees in Mediterranean areas: a simplified approach. *Agric. For. Meteorol*. 171-172, 93-103.

von Bloh, W., Schaphoff, S., Müller, C., Rolinski, S., Waha, K., Zaehle, S., 2018. Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). Geoscientific Model Development 11, 2789-2812.