SoilCare
SOILCARE FOR PROFITABLE AND SUSTAINABLE CROP PRODUCTION IN EUROPE

Report on the potential for applying soil-improving CS across Europe

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SoilCare

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Executive summary

European agriculture is confronted with a range of uncertainties regarding its future development. Some of these are linked to changing climatic and environmental conditions, while others are the result of our behaviour. Within the SoilCare project (https://soilcare-project.eu/) we aimed to explore different pathways for European agriculture, from now till 2050, as this will help to support the development of policies that are future proof. The main questions to answer in this report therefore become:

How can policies support sustainable farming practices under different future pathways?
Are some policy options more robust under a range of future pathways?

We used a combination of qualitative and quantitative techniques in a multi-actor approach to first develop scenarios that capture diverse pathways for European agriculture, secondly assess how agricultural practices can contribute to a European agriculture that is both sustainable and profitable within these pathways, and finally discuss what is needed to enable adoption and implementation of these practices. This report discusses the storyline, simulation and policy support approach developed as part of the project, the SoilCare Integrated Assessment model developed to carry out the impact assessment modelling at European scale in the project and used to quantify the storylines, and provides the developed qualitative and quantitative scenarios together with the policy options assessed against them.

Four scenarios were developed along policy-relevant axes (few or substantial challenges to voluntary instruments, and few or substantial challenges to mandatory instruments). Covering a matrix of substantial challenges to mandatory and voluntary instruments (Scenario: Race to the Bottom), substantial challenges to mandatory and few challenges to voluntary instruments (Scenario: Local & Sustainable), few challenges to mandatory and substantial challenges to voluntary instruments (Scenario: Under Pressure), and few challenges to both mandatory and voluntary instruments (Scenario: Caring & Sharing), both quantitative and qualitative techniques were applied to consider performance of SICS under a wide portfolio of drivers and policy responses.

The model results indicate that over time (until 2050), changes are expected in consumption, (domestic) production and net exports, yield, gross margin, soil organic carbon, and erosion. This is due to, amongst others, growth in population, changes in diets, trade flows, climate change, technological changes and changes in agricultural practices (i.e., through application of SICS). While some drivers are expected to result in impacts in the same direction in all scenarios (e.g., population growth is likely to lead to more consumption), other drivers could impact in very different ways. This is caused by regional differences, such as e.g., climate change impacting on yield levels and gross margins based on country specific crop prices and location specific biophysical conditions.

An important finding is that the Caring & Sharing (CS) scenario is likely to provide the best sustainability impacts (i.e., increased, or stable SOC contents and reduced erosion rates) and the Race to the Bottom scenario the worst.

Another important finding is that although the CS scenario leads to highest yield impacts, the gross margin of SICS uptake under this scenario is negative in many NUTS-2 regions. The most important factor contributing to this is the high implementation costs assumed when combinations of SICS are implemented. Despite sustainability being high on the agenda in the CS scenario, (financial) policy support will therefore likely be needed to enhance uptake of SICS. Alternatively, value added through additional products and services, and valuation of environmental co-benefits could be a pathway to widespread SICS adoption.

The cost-benefit analysis shows a mixed spatial pattern of scenarios that have the highest gross-margin across Europe. Reason for this is that the combination of drivers plays out differently in different parts of Europe, indicating the complexity of the issue and the importance of understanding local dynamics.

The participatory scenario development enriches the future pathways, while the modelling facilitates systems thinking and enhances the understanding of the causal relationships in space and over time. In the assessment of actions, the modelling is able to calculate the expected impact of policy options under various conditions, while the participatory activities allow to incorporate those assessment criteria that cannot be modelled, especially related to the socio-cultural and political aspects.

The combined participatory and modelling approach provides policy makers and other stakeholders with an enhanced understanding of the future uncertainties the agricultural sector and related value chains are confronted with. Better understanding plausible future pathways helps to design actions that target specific developments or are robust across developments. Actions that were deemed appropriate for specific developments include *labelling and certifications* and *lighthouse projects* under the scenarios Local & Sustainable and Caring & Sharing, and *consumer taxation* in Under Pressure and Race to the Bottom scenarios. No actions were identified that are robust across all scenarios, leading to the important conclusion that understanding the socio-economic conditions well is critical for policy design.

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1. Introduction

European agriculture faces a real challenge: it must reduce its negative environmental impacts but also remain competitive. A key area of concern is the ongoing degradation of agricultural soils, which is likely to increase further in the coming decades because of climate and socio-economic developments (European Environment Agency, 2019; Mission Board for Soil Health and Food, 2020). While there are well-known agricultural management techniques that can help to improve soil quality, uptake of these techniques remains low in Europe - despite various policy incentives (McNeill et al., 2018, 2020).

The SoilCare project studied the adoption of sustainable agricultural practices, in particular those related to improving soil quality. In this deliverable we report on the work carried out as part of Tasks 6.2 and 6.3 of the SoilCare project, which aim to further explore the biophysical, socio-economic, political, and technological factors impacting on adoption of these practices at the European scale. Knowing that these factors will change and interact over time in complex ways, bringing inherent uncertainties with them, we used a foresight approach to deal with these complexities and future uncertainties. The main questions to answer in this report therefore become:

1. *How can policies support sustainable farming practices under different future pathways?*
2. *Are some policy options more robust under a range of future pathways?*

To answer these questions, we have used a combination of qualitative and quantitative techniques in a multi-actor approach to develop scenarios for agricultural practices in Europe that are both sustainable and profitable. The developed scenarios provided input for identifying best policy actions, of which some were targeted to address issues in a specific future pathway, while others were found to be robust to facilitate sustainable practices under a range of pathways.

This report starts by providing an overview of the scenario, simulation and policy support process that has been applied (Chapter 2), followed by an overview of the SoilCare Integrated Assessment model developed as part of the SoilCare project to carry out the impact assessment modelling at European scale in the project and which is used to quantify the narrative scenarios (Chapter 3). Chapter 4 provides the results of the narrative scenarios developed, their quantification and the policy options that were found relevant and were assessed against the scenarios. This chapter concludes with a section demonstrating how future dynamics could be incorporated in the SICS Potential Index, elaborated on in D6.1. The report then concludes with the main findings and lessons learnt as well as some recommendations for future work.

2. Storyline, simulation, and policy support process

European agriculture is confronted with a range of uncertainties regarding its future development. Some of these are linked to changing climatic and environmental conditions, while others are the result of our behaviour. In this report we aim to explore different pathways for European agriculture, from now till 2050, and assess the impact of various policy options under each of them as this will help to support the development of policies that are future proof.

The process we applied, consists of 3 key elements:

- Development of storylines or qualitative scenarios for different future pathways for agriculture in Europe,
- Quantification of these storylines to assess the impact of the various pathways on sustainability and profitability,
- Development and assessment of policy options across the created pathways to facilitate a tailored and robust selection of options.

The approach we used to develop the pathways is called exploratory scenario development. In this approach we are not looking for the most likely future, nor are we deciding on a best or optimal future. We are interested in exploring the different uncertainties we might be confronted with, because by better understanding what might happen, we are in a better position to design effective policies. This means that we are aiming for a set of scenarios that help us scope a range of plausible future developments. The scenarios can therefore be rather extreme, but have to remain plausible. So basically, we try to think in structured ways about unexpected events, while avoiding scenarios that would be unrealistic.

The storyline, simulation and policy support process builds on the storyline and simulation approach (Alcamo, 2008; Van Delden and Hagen-Zanker, 2009; Riddell et al., 2019), which combines a participatory approach to develop storylines with simulation modelling in creating exploratory scenarios for the future. The approach was adapted to an agricultural context and enhanced with a policy support component to demonstrate the relevance of the scenarios in future-proofing policy options. This was accomplished by using the exploratory scenarios to enhance the understanding of future uncertainties resulting from climate change and socio-economic developments to test the robustness of policy options, or tailor options to reach objectives under specific conditions.

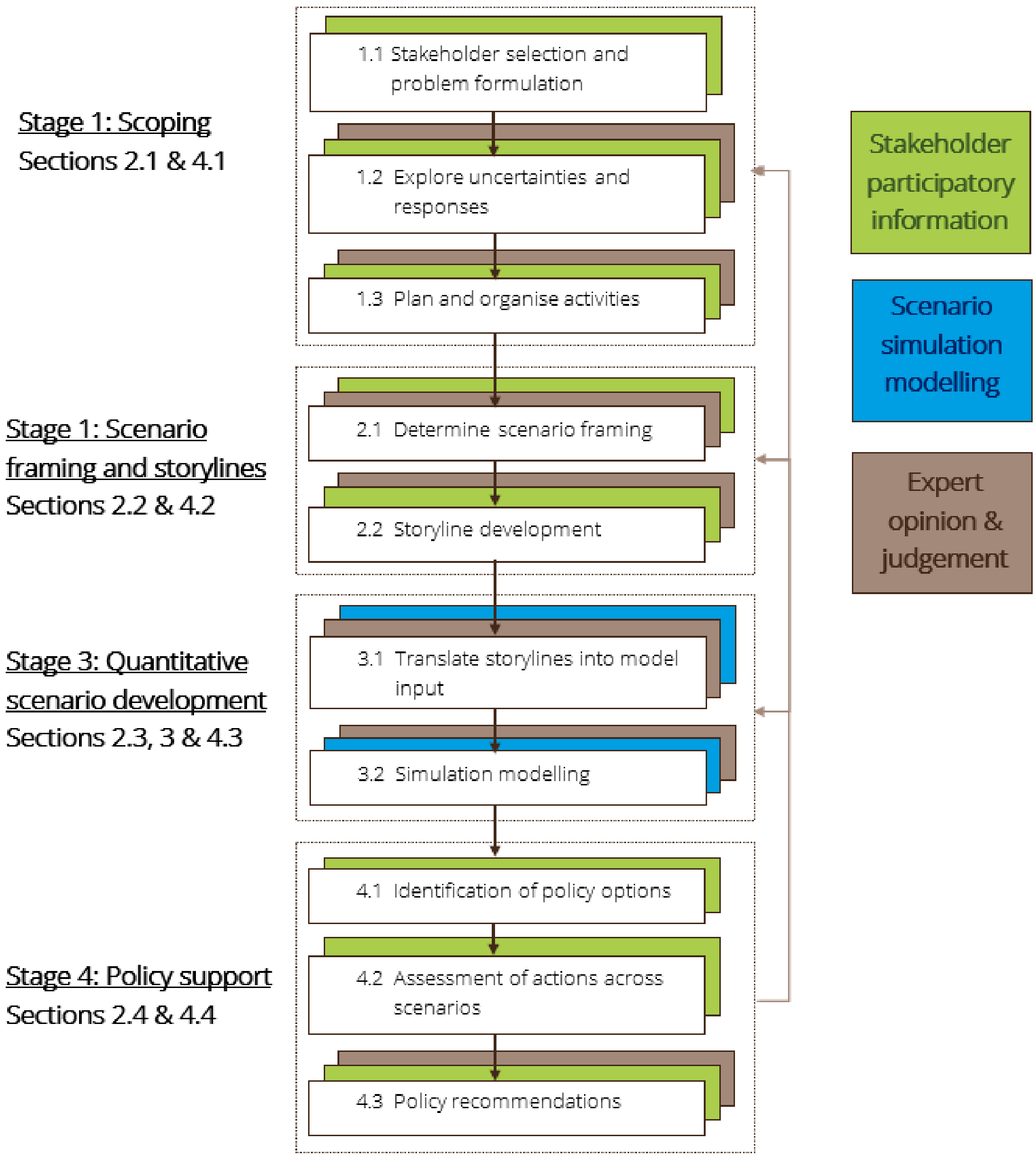


Figure 2.1: Overview of the storyline, simulation, and policy support approach

The exploratory scenarios include both qualitative and quantitative components, and the process we followed for developing our scenarios is one that included stakeholder participation, modelling and expert opinion and judgement to ensure scenarios are both relevant and contain useful levels of plausible detail. Figure 2.1 provides an overview of the entire process, which is divided in 4 stages, each again subdivided in smaller steps. Although the stages and steps are presented in a linear manner, it is important to allow for feedback and refinement of earlier tasks based on learnings throughout the process.

The figure shows for each step what tools and techniques are used to obtain results: stakeholder participation, modelling and/or expert opinion. For the stakeholder participation interviews, a webinar and 2 workshops were organised (see for more details Section 4.1). For the modelling we made use of the SoilCare Integrated Assessment Model (IAM), developed as part of the SoilCare project (see Chapter 3), and expert opinion was provided by the various project partners based on their respective background and expertise.

The next sections describe the various stages and steps of the storyline, simulation and policy support process. Each section discusses a different stage and starts with the main steps that are relevant in the particular stage, followed by the way the work was carried out in the SoilCare project.

2.1. Stage 1: Scoping

In this stage the scoping of the exercise takes place. This stage can be subdivided into three steps: Step 1.1 *Stakeholder selection and problem formulation* is about selecting the stakeholders to be involved, understanding the question(s) posed or problem(s) to be addressed, defining the objectives and deciding how progress towards them can be measured through a set of performance indicators. This is then followed by step 1.2 *Explore uncertainties and responses* in which we discuss what key drivers of change impacting on the context in which the problem is addressed and what their related uncertainties are, together with the policy responses that are or could be available to overcome or mitigate the problem(s) at present or in future. In the final step 1.3 *Planning and organising activities*, a decision is made on the aim of the participatory activities, the modelling, and the expert judgment as well as the ability and limitations of each tool and technique to support the overall process. With that information in mind, the use of each tool and technique is decided and planned for, ensuring alignment between them.

To obtain feedback on the above questions in the SoilCare project, we carried out a set of interviews with European stakeholders to better understand key drivers of change and related uncertainties, and key types of policy options that could be applied. Furthermore, we reviewed existing Europe-wide scenario studies in related fields.

Planning of the aim and timing of the various tools and techniques was carried out with partners from various work packages with different backgrounds, amongst which participation, modelling, policy and agronomy.

2.2. Stage 2: Qualitative scenario development

Stage 2 focuses on the development of qualitative scenarios. The framing of scenarios (step 2.1) is a critical component, as it provides the initial conditions and boundaries between alternate but equally plausible views of the future (Riddell et al, 2018). Commonly, a 2 × 2 matrix is applied as the scenario frame. This frame places two key driving forces for the future on the vertical and horizontal axes, and is commonly referred to as a 'standard' by practitioners and academics (Van Asselt, 2012). As this approach is often criticised due to difficulties in linking the scenarios with decision making (see e.g. Riddell et al., 2018 for a further discussion on this), we have used an adapted 2 x 2 matrix approach in line with the ones used by Kriegler et al. (2012) and Riddell et al. (2018), in which challenges to policy responses/options, in comparison to challenges to key drivers or uncertainties, are placed along the axes (see Figure 2.2). This approach focuses on identifying alternative futures in which policies are more or less effective.

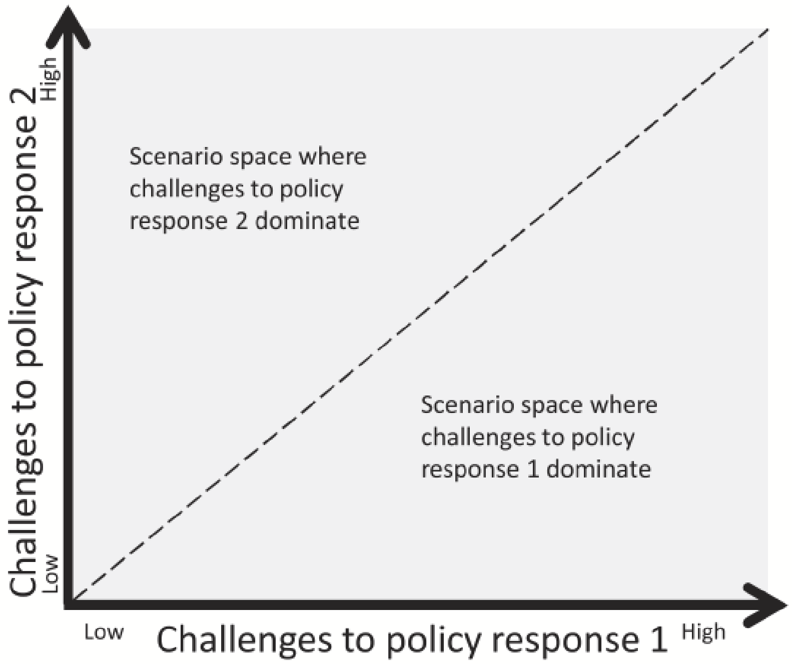


Figure 2.2: Scenario framing that places challenges to policy options on the axis to frame scenarios (Riddell et al., 2018).

The selection of the policy response axes in the SoilCare project was made based on the interviews from Stage 1. A first stakeholder workshop was next organised to start developing the storylines. To ensure consistency in the stakeholder group we invited interviewees from Stage 1 together with additional stakeholders from groups we felt were underrepresented. These additional stakeholders were also invited to take part in the interviews carried out as part of Stage 1 so all stakeholders had an equal opportunity to learn about the project and the process, and provide input to this before the start of the workshop. In addition to framing the scenarios, the interviews from step 1 also provided us with a first understanding of key drivers and related uncertainties, as well as key characteristics the scenarios should provide information on, which helped to shape the first workshop.

Once the scenario framing is decided upon and policy responses on each of the axes is set, Tasks 2.2 *storyline development* starts by understanding the key factors relevant to the policy responses. These factors are elicited by posing questions to stakeholders regarding their opinion as to what factors are most relevant to the framing of policy options and what makes them more or less difficult (Riddell et al, 2018). For each policy response axis, relevant factors should be discussed by participants, resulting in a decision on core factors relevant to the effectiveness of that policy response. The chosen factors are then used as the building blocks for creating the scenarios. For each scenario a storyline, or narrative, is next developed either through a participatory process or by experts. As part of this process, it is important to ensure the storylines provide sufficient information across various topics to sketch the context for the question(s) at stake and the simulation modelling. In case storylines are not developed by the stakeholders themselves, it would be important to provide them with the opportunity for feedback, to ensure the created storylines align with the building blocks developed in the participatory process and to build ownership for them in the remainder of the study.

As part of the SoilCare project, relevant factors for each of the policy responses were scoped and ranked in a workshop session. This was followed by exercises to better understand drivers of change and their uncertainties, which were then placed in a timeline to start the scenario development. For each of the four future pathways, a sustainability profile was created with associated expected uptake of sustainable agricultural practices. At the end of the day, exercises regarding the scenario consistency and validation were carried out and a general feedback moment was created for final comments. Using this information, a group of project partners then completed the storylines, which were next presented and discussed during a webinar. Although this webinar was organised because no in-person interactions were possible due to COVID-19, having an online event turned out to be very beneficial in reaching a much larger and more diverse audience with stakeholders participating from all over Europe. Based on feedback obtained during the webinar, storylines were fine-tuned.

2.3. Stage 3: Quantitative scenario development

In stage 3 of the process, we *translate storylines into model inputs* in step 3.1, and next run the model(s) to carry out a scenario impact assessment in step 3.2. *simulation modelling*.

In order to quantify the storylines, we need to extract those elements from the storylines that can be used to inform elements of the model. This approach follows the storyline and simulation approach as outlined in Alcamo (2008) and uses the C2I methodology outlined in Van Delden and Hagen-Zanker (2009). Here first *Clues,* or meaningful text fragments, are taken from the storylines, for which *Consequences* for the modelling are next described and finally these are used to set the *Impact* by selecting the model elements (inputs, parameters, equations) that need to be adjusted together with their numerical value to align with the storyline.

Using the settings per scenario, the impact of the different pathways on key performance indicators can next be assessed by the model(s). If possible, model results are presented to the stakeholder group, both to fine-tune them and better align them with the intention of the storylines, as well as to fine-tune the storylines based on the learnings from the simulation modelling (see e.g., Van Delden and Hagen-Zanker, 2009). The final scenarios then consist of the storylines and the model results, which complement each other.

As part of the SoilCare project, storylines were first compared based on their main characteristics. Next the *Clues* from the storylines together with the expected sustainability profile for each scenario provided the *Consequences* that could be modelled and the changes to model inputs and parameters to set their *Impact*. The settings for the 4 (socio-economic) scenarios were next simulated using the SoilCare IAM (see Chapter 3), thus providing an assessment of the sustainability and profitability impacts of each scenario. To incorporate climate change impacts, all scenarios were run with an RCP 4.5 scenario as little changes between different RCPs were expected over the duration of the simulation period (2020-2050).

The SoilCare project benefitted from developing the storylines and the integrated assessment model in the same project, as this helped to align both throughout their development.

Nonetheless difficulties were experienced due to the legacy models used as part of the SoilCare IAM.

2.4. Stage 4: Policy support

In the final stage, the combined results of the modelling and the narratives provided input for identifying best policy actions, of which some are tailored to different contexts and future pathways to target issues in those pathways, while others are robust under a range of pathways.

In the scoping phase of the process policy directions were discussed which are detailed in the step 4.1 of the final stage: *development of policy actions*. Using the developed scenarios, we aim to answer the question what actions should be taken to reach the objectives defined in the scoping stage within each of those scenarios. This activity is best suited to be carried out in a workshop in which participants discuss the question in a group setting. Next, in task 4.2 *assessment of actions across scenarios*, we assess if the policy options relevant for individual scenarios are also robust enough to be applied across two or more scenarios. The results from the above two steps are then in the final step 4.3 combined with the impact assessment modelling from stage 3 to provide *policy recommendations*.

In the SoilCare project an online workshop was organised to develop policy actions and assess them across scenarios. This information was used in the development of the policy recommendations in deliverable: *D7.2 Report on the selection of good policy alternatives at EU and study site level*.

3. SoilCare Integrated Assessment Model (IAM)

The SoilCare IAM has been developed as part of the SoilCare project and builds on earlier Europe-wide integrated assessment models developed in amongst others the FP6 LUMOCAP (Van Delden et al., 2010) and FP7 RECARE (www.recare-hub.eu) projects. The aim of the SoilCare IAM is to assess the impact of (a combination of) agricultural practices on profitability and sustainability, with a focus on soil quality. In order to do so, the SoilCare IAM consists of coupled models integrated into a policy support system. It allows the user to understand the impact of climate change and socio-economic developments on the future evolution of land use, management practices, vegetation and soil conditions. Furthermore, it provides users with the possibility to intervene in the system and assess the impact of policy, (spatial) planning and management options on profitability and sustainability indicators. The model was applied to Europe (EEA space) and includes 4 spatial levels: Europe, countries, NUTS-2 regions and local level. At local level the model operates on a grid of 100-500 m resolution. The socio-economic components operate at a yearly temporal resolution, while the hydrology and vegetation components operate on a monthly resolution. The time horizon is 2050.

An overview of the SoilCare IAM is provided in Figure 3.1. In brown the individual model components and their interactions with other model components are shown. Solid brown arrows indicate the information flow in the current time step, dashed arrows the information used as input for the next time step. The top blue box illustrates the types of scenario drivers for which the impacts can be assessed and the blue box at the bottom the types of policy-relevant information provided. The blue arrows on the left-hand side indicate where in the integrated model the scenario drivers impact.

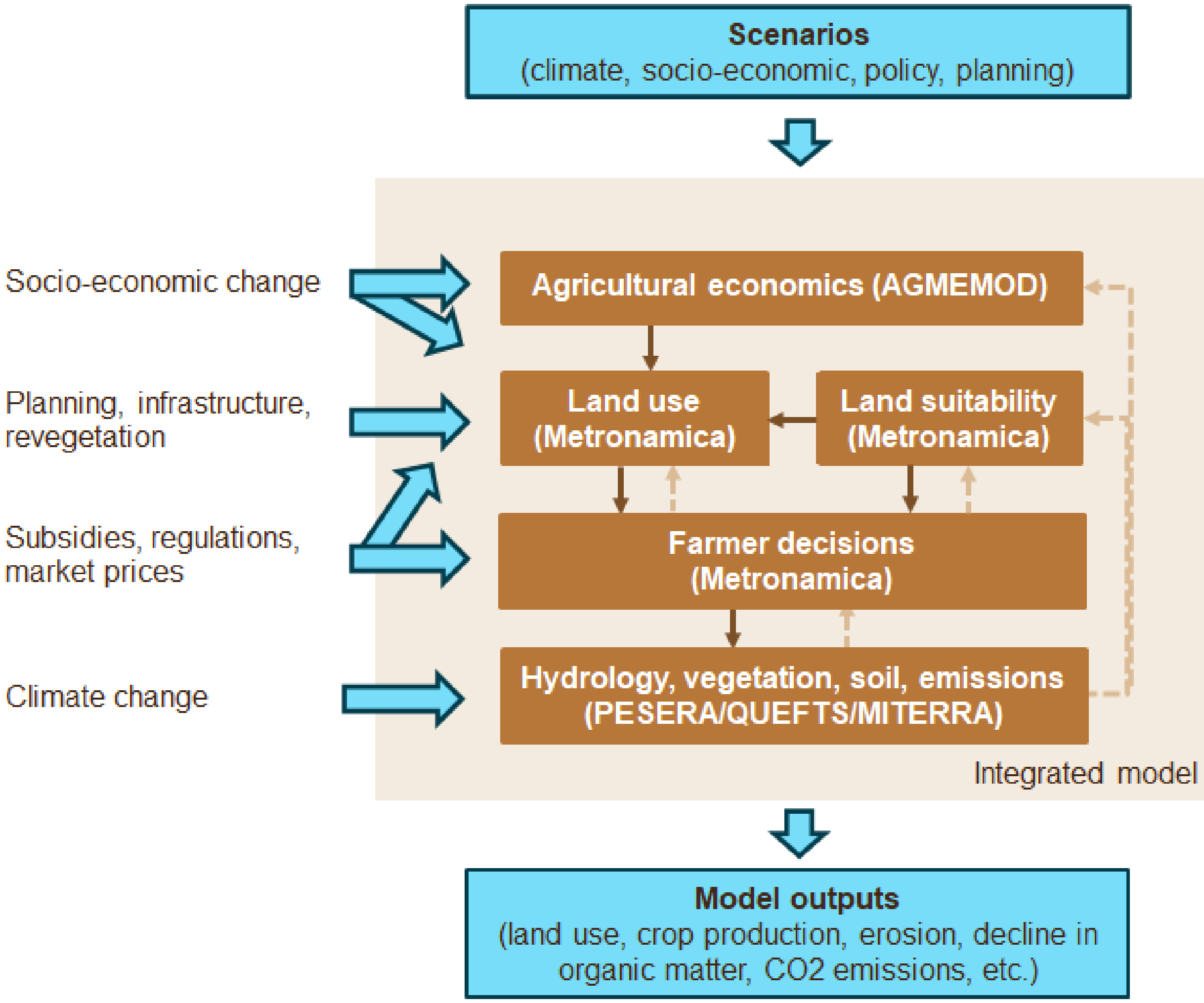


Figure 3.1: Overview of the SoilCare Integrated Assessment Model

As can be seen from the figure, climate change and socio-economic developments are key drivers of the SoilCare IAM. Whereas climate change impacts on the hydrology and vegetation growth, the socio-economic developments result in changes in agricultural profitability and land use, which together with farmers' decisions on land management provide a land use pattern with agricultural practices at grid-cell level. The biophysical models calculate the yield and the suitability of locations for land uses, crops and agricultural practices and this information feeds into the agricultural economics, land use and farmer decisions components. In this way, temporal changes to the soil quality and other biophysical conditions have an impact on the spatial distribution of future land use and management decisions. Using information on the cost of the practice, the yield, and the crop price, the IAM makes a cost-benefit assessment at local level. Likewise, the inclusion of biophysical models allows the calculation of sustainability impacts of land management decisions on SOM, erosion, and emissions.

In the following section more detail is provided about the individual models that are part of the SoilCare IAM: AGMEMOD, Metronamica, PESERA, QUEFTS and MITERRA.

3.1. Individual model components

3.1.1. AGMEMOD

AGMEMOD (Agriculture Member State Modelling) is an econometric, dynamic, partial equilibrium model covering up to 20 agricultural sectors, 17 food sectors and 11 fish sectors (Chantreuil et al., 2012). This model has been developed from 2001 onwards by a broad partnership including government agencies, research institutes and universities in the European Union as well as some other countries (e.g., Russia and Turkey) as a flexible tool (Salamon et al., 2019).

AGMEMOD operates at the member state level and relies on country-specific sub-models for EU member states, neighboring candidates, and a limited set of other countries. Specifically, AGMEMOD is based on a commodity-specific harmonized model structure template that is adapted by the responsible partners in the individual countries to their national characteristics. These country-specific models are subsequently integrated into an EU model, including a stylized version of the rest of the world (ROW), through multiple checks and feedback rounds (Salamon et al., 2019). AGMEMOD covers the major agricultural activities of each country and therefore the coverage of agricultural commodities varies between countries. Generally, AGMEMOD includes seven types of cereals (barley, oats, triticale, durum wheat, wheat, sorghum, corn), three types of oilseeds (sunflower seed, rapeseed, and soybean), sugar beet, protein crops, potatoes, apples, citrus fruits, and tomatoes (Salamon et al., 2019). Additionally, AGMEMOD includes live animals, as well as meats, raw milk and processed dairy products such as butter and cheese to represent the animal sectors. Based on the AGMEMOD model, base projections (business as usual) are generated and changes in policies or other drivers can be modeled. AGMEMOD currently provides projections up to 2030 (medium term market projections) on an annual basis. Projections related to agricultural crops are presented for area harvested, yield, production, use, trade, stocks and market prices (Salamon et al., 2017). Extrapolation has been used for simulations from 2030-2050.

An overview of the stylized market representation in AGMEMOD is shown in Figure 3.2 (Salamon et al., 2017; 2019). The endogenous variables are estimated through equations describing the behavioral responses of economic agents to changes in market prices, policy instruments, and other exogenous variables, and changes in lagged endogenous variables. Parameters of behavioral equations are econometrically estimated from time series data (from EUROSTAT sources and national statistics) or are set relying on expert knowledge and literature. These equations represent the supply side through beginning stocks, production and imports, and the demand side through domestic use, exports and ending stocks. Within a single commodity market and within any given year, supply is set equal (or in equilibrium) to demand. Moreover, these balances must hold for each product at the EU and Member State level to solve the modelling system in prices, taking the international trade and other commitments of the EU into account. The stylized ROW model then assumes market equilibrium for each commodity at the global level. In this approach, international prices are formed by closing global balances. Furthermore, domestic markets can be linked to each other on the supply or demand side (complementarity or substitution). The demand for feed-component provides the link between the crops and livestock sub-models. More details on the AGMEMOD model and its calibration can be found in Chantreuil et al. (2012) and Salamon et al. (2017; 2019).

Generally, AGMEMOD is mainly used for baseline, i.e., business-as-usual, projections, for example contributing to the yearly EU agricultural outlook of the European Commission (Salamon et al., 2019). Furthermore, it has been used to simulate and analyze the impact of agricultural policy changes as well as accession of countries to the EU.

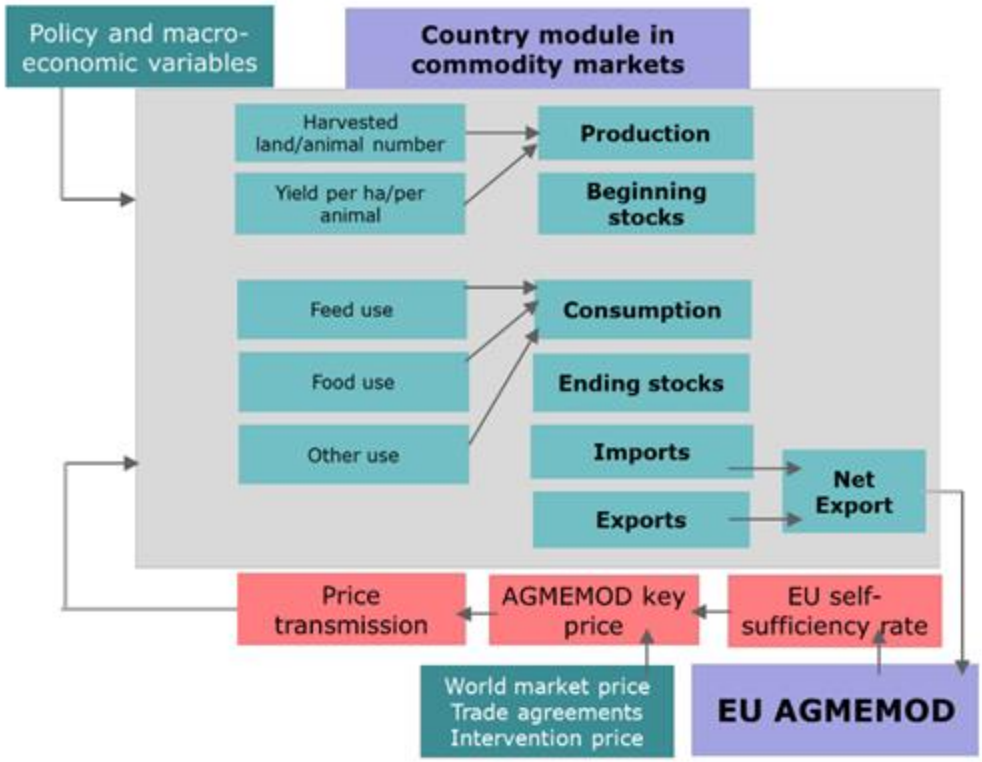


Figure 3.2: Stylized market representation in AGMEMOD (source: Salamon et al., 2017)

3.1.2. Metronamica

Metronamica (Van Delden and Hurkens, 2011; RIKS, 2017; www.metronamica.nl) is a generic forecasting tool for planners and policy analysts to simulate and assess the integrated effects of policy measures on urban and regional development. The system interactively simulates the impact of a variety of external influences (e.g. macro-economic changes, population growth, etc.) and policy measures (e.g. land use zoning, conservation policies, densification policies, etc.) on the regional development of a city, region, country or continent. With the integrated scenario support, what-if analyses can be performed that help evaluate alternative plans under various external conditions.

The core of Metronamica is a cellular automata (CA)-based land use allocation component that simulates land use development over time based on a 'competition for space' principle. Based on their economic and political power, actors will be able to occupy the locations which are most desirable for them. These behavioural dynamics can be facilitated or countered by planning and policy interventions in obtaining a more desirable future. Metronamica is equipped with a set of indicators to assess how autonomous developments shape long-term land use dynamics and how (combinations of) policy options impact on these future pathways.

Metronamica is developed using the Geonamica software environment (Hurkens et al., 2008). Applications can be set up with one, two or three spatial levels depending on their scope. Spatial resolution at local level varies for current applications between 25 m. and 1000 m. Temporal resolution is a year. Temporal horizon is 20 to 50 years into the future.

Overview of model components

The models that are incorporated in Metronamica simulate activities that take place at four spatial scales: global, national, regional and local, where global refers to the entire simulated area, being Europe (EEA space) in the SoilCare IAM. At global level forecasts or scenarios about development in population, jobs and agricultural demand are entered as exogenous drivers. These figures are then used as an input for the national and regional model.

At the national and regional level, socio-economic changes take place based on the relative attractiveness of regions and the costs required to travel from one region to another. This provides the basis for the distribution of European and national growth as well as migration of jobs and people over countries and regions. This is furthermore input for the allocation of activities within the regions.

On the local level, land use demands from the regional model are allocated to grid cells based on several elements including local accessibility, physical suitability, zoning regulations and the attraction, repulsion and competition between different land use functions. Finally, the local biophysical and socio-economic characteristics feed back into the attractiveness at the regional level.

For each application, the user can select one or more model components. Based on the selection of components, inputs for them come from other components or are defined as exogenous drivers.

The different components and their interactions are schematised in the system diagram of Metronamica in Figure 3.3. The processes modelled in the components are briefly described in the paragraphs below, with emphasis on the regional model and especially the land use model as these are applied as part of the SoilCare IAM. More information including the equations used can be found in the Metronamica model description (RIKS, 2017).

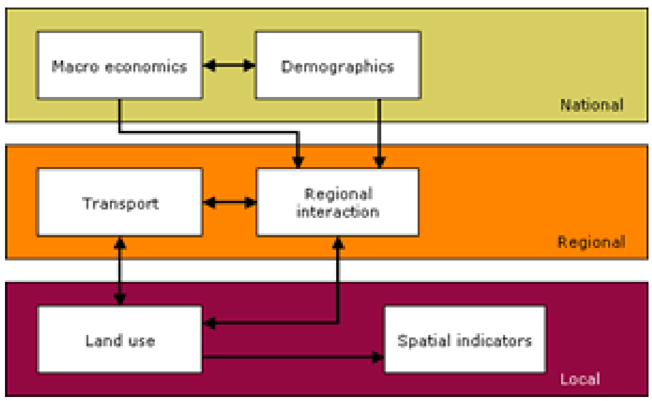


Figure 3.3: Metronamica system diagram

Regional model

The regional model is an integral part of the Metronamica land use modelling framework (Van Delden & Hurkens, 2011; RIKS, 2017). It is a spatial interaction model that has been used in a large number of previous projects and products around the world (Environment Explorer, Xplorah, MOLAND, LUMOCAP, RECARE IAM). In the SoilCare IAM it is used to allocate population and jobs from European level to national level and from national level to regional model.

The regional model applied here models the levels of activity in different socio-economic sectors together with their land demand. These in turn form a restriction on the cell allocation algorithm of the land use model. Specifically, the levels of activity are converted to a number of cells that needs to be allocated to each land use function by the land use model. The level of activity in a sector and region can be expressed in terms of the number of jobs, if we are dealing with an economic sector, or in terms of the number of people, if we are dealing with a population sector.

The allocation of the growth amongst the regions depends to a large extent on the relative attractiveness of each of the regions. In modelling the distribution of the national socio-economic growth and migration, distance also plays a crucial role. The underlying assumption for this is that regions can benefit from other attractive regions, as long as the distance is not too large. Furthermore, people and jobs are reluctant to migrate over greater distances.

The attractiveness for the socio-economic sectors (population, jobs in main economic sectors) is based on the existing socio-economic activity in the study area as well as regional and local characteristics. Local characteristics that can be taken into account are the suitability for different land use functions, the available space and the local accessibility.

Land use model

The land use model applied in SoilCare is an integral part of the Metronamica land use change modelling framework (Van Delden & Hurkens, 2011; RIKS, 2017; www.metronamica.nl), see also Figure 3.4. In the Metronamica land use model, the entire modelling area is represented as a mosaic of grid cells, each occupied with a specific land use. All cells together constitute the land use pattern of the study area. The underlying concept of the model is that land use dynamics are driven by a competition for space. In principle, it is the relative attractiveness of a cell as viewed by a particular spatial agent, and together with its (economic and political) power, the inertia of the land use and the local constraints opportunities that cause cells to change from one type of land use to another. Changes in land use at the local level are driven by four important factors:

- Physical suitability, represented by one map per land use. The term suitability is used here to describe the degree to which a cell is fit to support a particular land use function and the associated economic or residential activity for a particular activity. Suitability maps are constructed based on physical characteristics of the location. Suitability maps remain constant during the simulation unless new suitability maps for specific times are imported.

- Zoning or institutional suitability, represented by one map per land use function modelled. Zoning maps are used for enforcing spatial restrictions on the allocation of land uses. For each land use there is a time-series of zoning maps, specifying the institutional restrictions posed on a location. For each class within each zoning, map settings are provided on the restrictions for the various land uses, thus making some locations strictly restricted for e.g., urban and agricultural land uses, while other locations might only be restricted for urban land uses, while agricultural activity is still allowed, or experiences only minor restrictions. Besides restricting certain developments, it is also possible to actively stimulate certain developments, such as dedicated locations for urban expansion or agriculture. These restrictions and stimuli can be set for different periods of time. Zoning maps remain constant during the simulation unless the user predefines their changes or changes them throughout the simulation.
- Accessibility, represented by one map per land use function modelled. Accessibility is an expression of the ease with which an activity can fulfil its needs for transportation and other infrastructure in a particular cell based on the infrastructure network. The accessibility is calculated per land use function and only changes based on changes to the infrastructure network or the accessibility coefficients (the importance of different land use functions to be close to different elements of the network) in the land use model.
- Dynamic interaction of land uses and related activities in the area immediately surrounding a location is represented by the neighbourhood potential. For each land use function, a set of spatial interaction rules determines the degree to which it is attracted to, or repelled by, the other functions present in its surroundings; a 196 cell neighbourhood. If the attractiveness is high enough, the function will try to occupy the location, if not, it will look for more attractive places. New activities and land uses invading a neighbourhood over time will thus change its attractiveness for activities

already present and others searching for space. This process constitutes the highly non-linear character of this model.

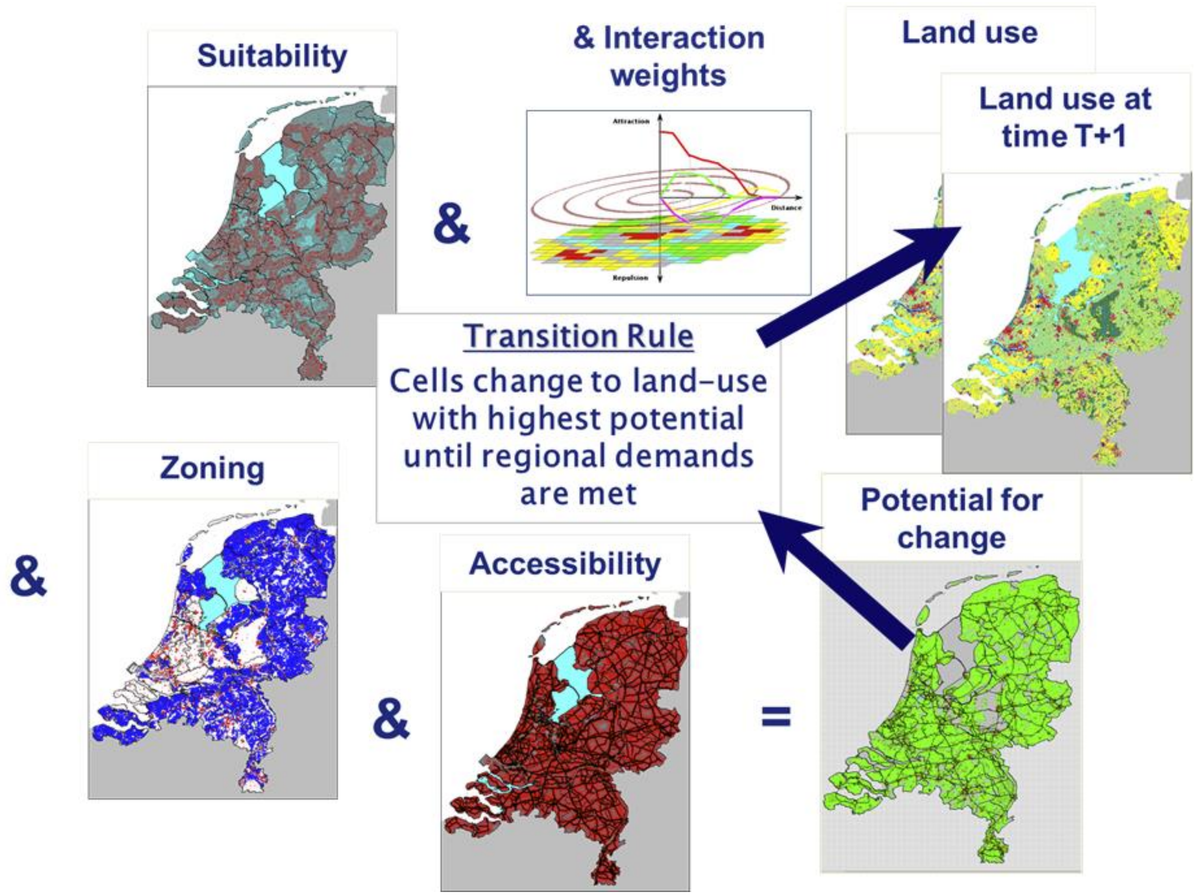


Figure 3.4: Metronamica land use model

On the basis of these four elements, the model calculates for every simulation step the transition potential for each cell and function. In the course of time and until regional demands (provided by the user or calculated in the regional model) are satisfied, cells will change to the land use function for which they have the highest transition potential. Consequently, the transition potentials reflect the pressures exerted on the land and thus constitute important information for those responsible for the design of sound spatial planning policies.

Farmer decisions' model

Within the agricultural areas the farmer decisions' component provides the crop choice and land management practices on each individual plot. There are two options for running this component: 1) farmer decisions are made by the model by simulating the farmer decision process. This option builds on the RECARE Farmers' decision model, and 2) the user enters external information on crop choices and farm practices, for which the former will be allocated by the land use model and the latter in this component according to the rule set provided for them.

The **first option** builds on the farmer decisions' model incorporated in the RECARE IAM and developed as part of the RECARE project, building on the MedAction and DESMICE models (see Van Delden et al., 2018). In this option a farmer is assumed to make a decision on each 100-500 m. cell within the agricultural areas. The locational characteristics are an important input into this decision. Locations with a high suitability are valued due to the high yield they can produce, while accessible locations are favourable because of their easy access to a market. Suitability maps for each crop type are provided by the Land Suitability component and include factors such as soil type, soil conditions (e.g., soil organic matters contents, soil depth) as well as climatic factors. Accessibility is based on the assumed travel times to a market and includes the distance to roads and markets.

For each location the profit for the farmer is calculated using the crop on the field, the yield calculated by the biophysical model, and the costs and benefits. In addition, for possible substitute crops the profit is calculated using the suitability layers and the costs and benefits for the substitute. Based on the profit margin of the current crop and the profit margins or the substitute crops, the farmer will then take a decision to continue with the current crop or switch to a different crop type. This decision is simulated using a probabilistic approach where the probability to change depends on the difference in profit margin and the social characteristics of the farmer determining how likely to change he/she will be. When profit margins are negative over a few years, a farmer can also abandon the plot. In that case the plot will become part of the natural vegetation area in the land use model in the next year. To avoid decisions being taken on one bad or good year, we work with a 3-year weighted average in the crop choice decision process.

Once the crop choice has been made, the farmer assesses the relevant management practice. European-wide applicability layers for each practice have been developed and based on these and the selected crop type a selection of measures is taken into consideration. Based on the cost-benefit ratio of the measures and the social characteristics of the farmer a practice is selected.

The **second option** was developed as part of the SoilCare project and allows to work with external crop demands and test out the impact of a selection of management options. In this option, external crop demands are allocated from national or regional level using the same process as the land use allocation in Metronamica. Regarding the management practices, the user can define a set of practices as well as the percentage of farmers growing a specific crop that will apply this practice.

Regardless of the option selected, maps with crop types and management practices are next forwarded to the biophysical model for calculation of the yield and the impacts on the soil.

3.1.3. PESERA

The core model simulating the biophysical processes in the SoilCare IAM is the Pan-European Soil Erosion Risk Assessment (PESERA) model. The PESERA model offers an erosion risk assessment at (multi)national scale (Kirkby et al, 2008). The model's robustness and flexibility has been demonstrated through its performance at different resolutions and across different agro-ecological zones. The model's main output are monthly spatial maps of vegetation biomass, soil humus content, erosion, runoff and soil water deficit.

Model rationale and process description

A shortened technical description is given here, based on Kirkby et al. (2008), where all details can be found. PESERA is a process-based and spatially distributed model designed to estimate long-term average erosion rates by combining the effect of topography, climate and soil properties. A schematic model structure is provided in Figure 3.5. The model is built in three conceptual stages:

1. A storage threshold model to convert daily rainfall to daily total overland flow runoff.
2. A power law to estimate sediment transport from runoff and gradient. The model interprets sediment transported to the base of a hillslope as average erosion loss.
3. Integration of daily rates over the frequency distribution of daily rainfalls to estimate long-term average erosion rates.

In the first step, a simple storage or bucket model is used to convert daily rainfall into daily overland flow runoff, which is estimated as the rainfall minus the threshold storage. The threshold storage depends dynamically on soil properties, vegetation cover and soil moisture status, varying over the year. The most important soil factors that determine the threshold storage beneath the vegetation-covered fraction of the surface are texture, depth (if shallow) and organic matter. Where the surface is not protected by vegetation, the susceptibility of the soil to crusting and the duration of crusting conditions generally determine a lower threshold. The final threshold is a weighted average from vegetated and bare fractions of the surface.

Corrections are made for the soil water deficit, which may reduce the threshold where the soil is close to saturation.

Transpiration is used to drive a generic plant growth model for biomass, constrained as necessary by land use decisions, primarily on a monthly time step. Leaf fall, with corrections for cropping, grazing, etc., also drives a simple model for soil organic matter.

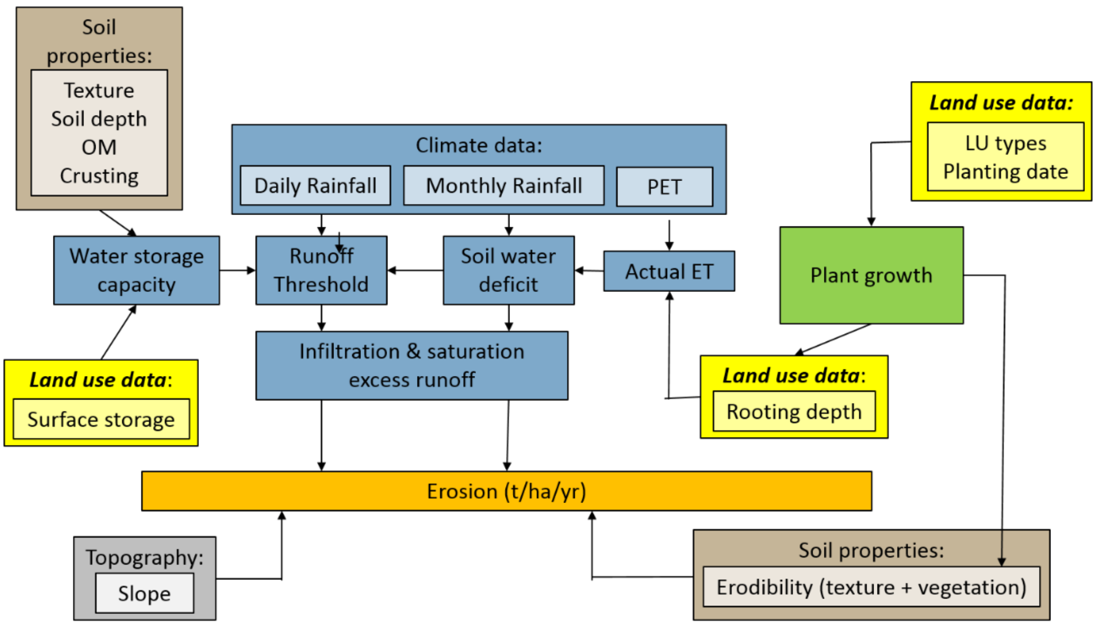


Figure 3.5: Schematic overview of processes in the biophysical model component

Precipitation is divided into daily storm events, expressed as a frequency distribution. The distribution of daily rainfall totals has been fitted to a Gamma distribution for each month. The rainfall distribution, reflected by the coefficient of variation of rainfall per rain day is given for each month of the simulation period and may be adapted for (future) climate change scenarios. Daily precipitation drives infiltration, excess overland flow and soil erosion, and monthly precipitation, driving saturation levels in the soil. Infiltration excess overland flow runoff is estimated from storm rainfall and soil moisture. Sediment transport is then estimated using a power law approach driven by erodibility, gradient and runoff discharge. Estimates of sediment transport are based on infiltration excess overland flow discharge. In the PESERA model, sediment transport is interpreted as the mean sediment yield delivered to stream channels and includes no allowance for downstream routing within the channel network. The PESERA model includes three terms:

- Soil erodibility, which is derived from soil classification data, primarily interpreted as texture (Le Bissonnais et al., 2002).
- Local relief, which is derived from DEM data as the standard deviation of elevation within a defined radius around each point.
- An estimate of accumulated runoff, which is derived from a biophysical model that combines the frequency of daily storm sizes with an assessment of runoff thresholds based on seasonal water deficit and vegetation growth.

Finally, to obtain long-term estimates of soil erosion these estimates must then be scaled up by integrating over time. This process of scaling up has two stages; first from momentary to event-integrated dependence, and secondly from events to long-term averages via the frequency distribution.

The role of vegetation and soil organic matter can modify the infiltration rates through changes in soil structure and/or the development over time of surface or near-surface crusting. Three models are coupled to provide the dynamics of these responses: (i) an 'at-a-point' hydrological balance, which partitions precipitation between evapotranspiration, overland flow, subsurface flow and changes in soil moisture; (ii) a vegetation growth model, which budgets living biomass and organic matter subject to the constraints of land use and cultivation choices; and (iii) a soil model, which estimates the required hydrological variables from moisture, vegetation and seasonal rainfall history.

Biomass output from the PESERA model can be directly used to estimate the vegetation biomass of a pixel of a given land cover category. Its carbon content can be assessed through a carbon factor. For agricultural crops, water-limited yield can be estimated by multiplying biomass with a harvest index.

3.1.4. Dyna-QUEFTS

Whereas the vegetation model component in PESERA simulates the impact of water availability, specific consideration is also given to nutrient limitations by building in Dyna-QUEFTS, a spatially-explicit and dynamic version of the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model (Janssen et al., 1990). Nutrient limitations are important in many locations across Europe. Moreover, land management systems often include higher use of inputs, which helps generate higher yields which would not be captured if nutrient availability and uptake are not explicitly considered.

QUEFTS was initially developed for quantitative evaluation of the native fertility of tropical soils, using calculated yields of unfertilized maize as a yardstick. In the past decade, QUEFTS has been adapted to improve its global applicability, including in temperate zones (Sattari et al., 2014). It can also consider nutrients applied by the land user, and the model has been successfully parameterised to cover other crops next to maize (Sattari et al., 2014).

The procedure consists of four successive steps (Figure 3.6). First the potential supplies of nitrogen, phosphorus and potassium are calculated, applying relationships between chemical properties of the 0-20 cm soil layer and the maximum quantity of those nutrients that can be taken up by a crop, if no other nutrients and no other growth factors are yield-limiting. In the second step the actual uptake of each nutrient is calculated as a function of the potential supply of that nutrient, taking into account the potential supplies of the other two nutrients. Step 3 comprises the establishment of three yield ranges, as depending on the actual uptakes of nitrogen, phosphorus, and potassium, respectively. Next, these yield ranges are combined in pairs, and the yields estimated for pairs of nutrients are averaged to obtain an ultimate yield estimate (Step 4).

In the Dyna-QUEFTS model the above-mentioned four steps are calculated for grid cells in a map instead of a single point. Furthermore, N supply is through the SOM map of the PESERA model, and in a fifth step of the model P and K supply in the soil is updated due to nutrient additions and subtractions in the respective time step.

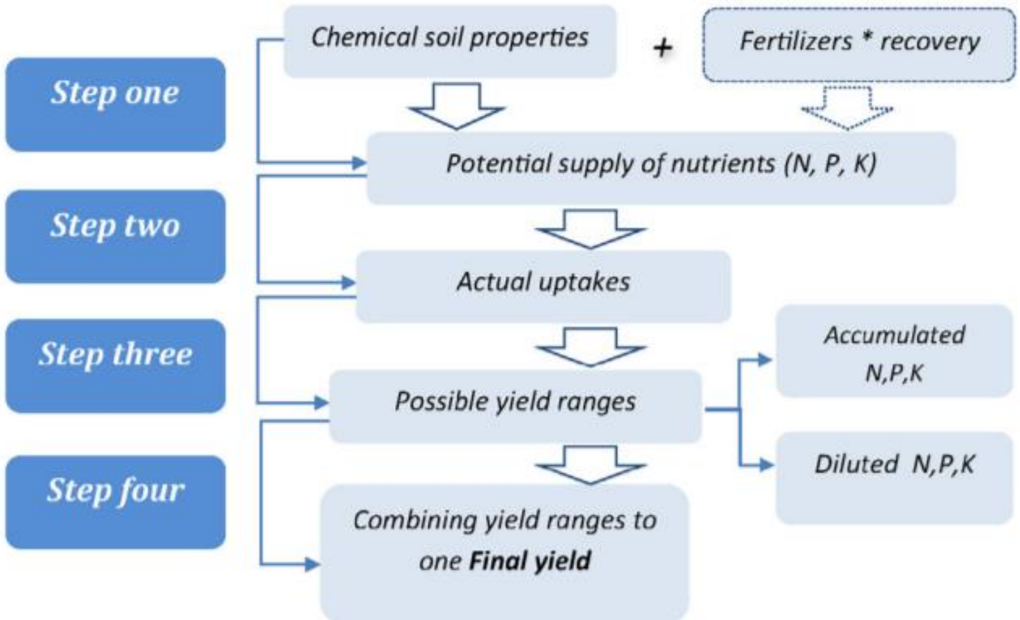


Figure 3.6: The four steps in the simulation procedure of QUEFTS (Source: Sattari et al., 2014).

Dyna-QUEFTS uses maps on soil nutrient data as input, together with temperature, pH, maximum yield and fertilizer applications and recovery fractions. It outputs nutrient-limited crop yield. Details of the Dyna-QUEFTS model can be found in (Fleskens et al., 2020). Here, it has been further adapted by considering further crops (wheat, rice, pulses, sugarbeet, potato and oilseeds) and nutrient cycling processes (atmospheric N and K deposition and N fixation).

The final yield calculated in the biophysical models is assumed as the minimum of water-limited (PESERA) and nutrient-limited (QUEFTS) yield.

3.1.5. MITERRA

MITERRA-Europe is a deterministic emission and nutrient flow model, which calculates greenhouse gas (CO_2, CH_4 and N_2O) emissions, nitrogen emissions (N_2O, NH_3, NO_x and NO_3), N and P flows, soil organic carbon stock changes and soil erosion on annual basis, using emission factors and leaching fractions. The model was developed to assess the effects and interactions of policies and measures in agriculture on N losses on a NUTS-2 (Nomenclature of Territorial Units for Statistics) level in the EU-28 (Velthof et al., 2009; de Vries et al., 2011). The MITERRA-Europe model was originally based on the models CAPRI (Common Agricultural Policy Regionalised Impact), and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies), and was supplemented with a N leaching module, a soil carbon module, and a module for greenhouse gas mitigation measures. In addition soil erosion by water is calculated following the Revised Universal Soil Loss Equation (RUSLE) approach (Panagos et al., 2015).

Input data consist of activity data (e.g., livestock numbers and crop areas and yield from CAPRI, Eurostat and FAOSTAT), soil data (LUCAS), climate data (WorldClim), GHG emission factors (IPCC, UNFCCC), and NH_3 emission factors, excretion factors and manure management system data (GAINS, UNFCCC). The model includes measures to simulate carbon sequestration and mitigation of GHG and NH_3 emissions and NO_3 leaching. For soil carbon, the calculation rules of the well-known soil carbon model RothC are used (Merante et al., 2014). RothC (version 26.3; Coleman et al., 1997; Coleman and Jenkinson, 2014) is a model for the turnover of organic carbon in non-waterlogged soils that takes effects of soil type, temperature, moisture content and plant cover on the turnover process into account. It uses a monthly time step to calculate total organic carbon on a year-to-century timescale. In the RothC model, SOC is split into four active compartments and a small amount of inert organic matter. The four active compartments are decomposable plant material, resistant plant material, microbial biomass and humified organic matter. Each compartment decomposes by a first-order process with its own characteristic rate. The MITERRA-Europe model is described in more detail in Velthof et al. (2009) and Lesschen et al. (2011) and the most recent input data is described in Duan et al. (2021).

3.2. Policy support

3.2.1. User interface

An important task for the developer of an integrated assessment model (IAM) is to bridge the gap from scientific tools to user-friendly systems, by creating a graphical user interface (GUI) that is easy to use and guides users in the steps that need to be taken to carry out a scenario or policy impact assessment study. In addition, as IAMs often encompass complex models, the user interface should provide insight into the structure and functioning of the model and provide access to all relevant model inputs and outputs for updating the data, calibration and validation. Trying to incorporate both in one interface often leads to a system that is confusing for any user.

In the design of the SoilCare user interface we decided that the interface should be able to provide access to two different types of users: the policy analysts who use the system as part of their policy process and who carry out scenario and impact assessment studies with the model, and the scientists or modellers who can update the underlying data and parameters and possibly even the model equations. For the latter group of users, we created the modeller interface where elements are grouped per model; each individual model has its own access point through the system diagram. Access to settings for the policy user is structured according to their logical function in the policy interface. On a high level, access is organized by the steps that a user takes to carry out an impact assessment analysis: configure drivers, create integrated scenarios, run the simulation, review output through the indicators and do comparative analysis. Zooming in on those parts, we grouped settings and outputs by their type and their domain; for example, all economic policy measures together, all external factors together, all ecological indicators together etc.

3.2.2. External drivers, policy options and indicators

The SoilCare IAM includes climate change, population growth and macro-economic developments as main external drivers for which the impact can be assessed. Selecting a specific climate scenario, impacts on the inputs into the hydrology, the vegetation and the land suitability models. Entering a future scenario (trendline) for population and/or jobs impacts on the national and regional activity levels, as well as in the demand for residential and urban economic land. Entering market price scenarios will impact on the crop choices farmers will make.

By running the model with different climate and socio-economic scenarios an understanding is built of the future uncertainties planners and policy makers are faced with as well as the implications of these scenarios on the status of the land, the vegetation, the soil, the soil threats and the ecosystem services if these scenarios would materialise.

To assess the impact of the scenarios, a set of indicators is incorporated. These consist of indicators providing information about the state of the system:

- Land use
- Vegetation cover (-)

As well as indicators providing information on profitability:

- Yield (tonnes/ha)
- Cost-benefit of management practices (€)

And indicators providing information about sustainability:

- Water erosion risk (tonnes/ha/yr)
- Changing SOM state (kg/m^2) and related SOM decline risk (ordinal classification)
- Soil carbon sequestration

- Nitrate leaching risk (kg/ha)
- N leaching and runoff
- Saving on N fertilization
- Soil nitrogen balance
- Nitrous oxide (N2O) emission
- Ammonia (NH3) emission
- Soil sealing (probability for urbanisation)
- Decline in ecosystem services supply potential due to urbanization

In order to improve soil health and mitigate the impact of external drivers on soil threats or decline in ecosystem services supply, different policy, planning and management options can be selected. In the current version of the SoilCare IAM the following options are included:

- Spatial planning (zoning, e.g. NATURA 2000)
- Infrastructure development (road, train, irrigation)
- Revegetation
- No tillage and minimum (or reduced) tillage
- Mulching
- Cover crops
- Stubble management
- Increasing the surface soil water storage
- Compaction reduction
- Set/change nutrient quantities (e.g., reduced fertiliser applications)

- Change nutrient efficiencies
- Change nutrient types (e.g., from chemical fertilizer to organic amendments)

When running the IAM to explore plausible future scenarios, farmers will make decisions on the management they apply on their plot based on the biophysical conditions of their plot resulting in a specific yield and a related profit (or loss). A policy user can explore how to stimulate more sustainable practices by providing (more) subsidies for them. He/she can also explore the implications of limiting urban sprawl through spatial planning or try to redirect growth away from high quality soils with infrastructure investment. The impact of these measures can then be assessed through the indicators listed above. The SoilCare IAM includes a set of tools to compare various scenarios or assess the changes within a scenario.

In addition to running the SoilCare IAM with the farmers behavioural component activated, it is also possible to address questions such as: what if X% of all farmers would switch to sustainable practices? Or what if all cereal farmers switch to practice Y? Although these scenarios are not meant to provide a realistic picture of the future they do help to understand the impact of changed practices.

3.3. Key model improvements as part of SoilCare

As part of the SoilCare project work has been carried out on individual models, the integration between components and the underlying software environment. Key improvements carried out during the project include:

- A procedure has been developed to convert AGMEMOD results into land demands meeting the logic of the developed scenarios.
- A new land use map for 2018 has been created to ensure alignment between the various crop types used in the models including the in SoilCare IAM
- The Europe-wide version of Metronamica has been updated to a new start year (2018) and calibrated for this new start year.

- The Europe-wide application of the FORTRAN equilibrium version of PESERA has been updated to a new year (2018) using new data and an improved calibration. Updated historic climate data has been prepared as input for PESERA and was used to obtain equilibrium information on key variables for the simulation version of the model.
- The C++ simulation version of PESERA has been applied to and calibrated for Europe. As part of this an approach was developed and applied to provide erodibility information for the Northern countries (Norway, Sweden and Iceland) to solve issues with existing Europe-wide data, see also Annex 2 PESERA, and two climate scenarios (RCP4.5 and RCP8.5) have been prepared as monthly input data for the future simulations (2018-2050).
- Additional crop types have been added to PESERA and these have been parameterised and calibrated for different climate zones in Europe.
- PESERA is expanded with an option to include irrigation at cellular (plot) level impacting on the soil water deficit and hence the yield.
- PESERA is expanded with an option to define management options (SICS) by setting sets of parameter values; a set of management practices has been defined and calibrated.
- PESERA is expanded with an option to set crop parameters per climate zone.
- The QUEFTS model has been applied to Europe for the first time and has been calibrated for inclusion of a range of European crop types.
- The QUEFTS model has been expanded with an option to set inputs and calibration parameters per country or region.
- Farmer decisions component is expanded with an option for the user to set management options.
- The GEONAMICA software environment has been enhanced so the entire SoilCare IAM application for Europe can run at the same time and GUI components have been developed or adapted in line with new model developments of individual components.
- A set of software tools and procedures has been developed to facilitate the updating of model parameters across Europe for different scenarios and to facilitate the analysis of results.

3.4. Using the SoilCare IAM in the project

The SoilCare IAM includes 37 countries: the European Union countries, Albania, Bosnia-Herzegovina, Iceland, Kosovo, North Macedonia, Norway, Montenegro, Serbia, Switzerlandand, UK and operates at a spatial resolution of 100-500 m. grid cells. For the SoilCare project the temporal horizon is set to 2050. Models operate at a temporal resolution of months and years in line with the processes they represent.

The SoilCare IAM includes a range of agricultural and non-agricultural land uses and crop types:

- Arable crops and land uses: winter cereal, spring cereal, grain maize, fodder maize, rice, pulses, sugarbeet, potato, oilseed, vegetables & flowers, industrial crops, fallow.
- Permanent crops and land uses: Nurseries, vineyards, fruit trees and berry plantations, citrus fruits.
- Grass and grazing lands: natural grasslands, temporary grasslands, leguminous plants harvested green.
- Forest land uses: broad-leaved forest, coniferous forest, mixed forest.
- Urban land uses: urban fabric, industrial or commercial units, green urban areas and leisure, road and rail infrastructure, port areas, airports, mining and dump sites,
- Natural uses: beaches, open spaces with little or no vegetation, inland marshes, peat bogs, maritime wetlands, inland waters and marine waters.

Not all crop types and uses can or need to be used by all models. An overview of how the different land uses and crop types link throughout the different models is provided in Annex 1. The base map of the SoilCare IAM is provided in Figure 3.7.

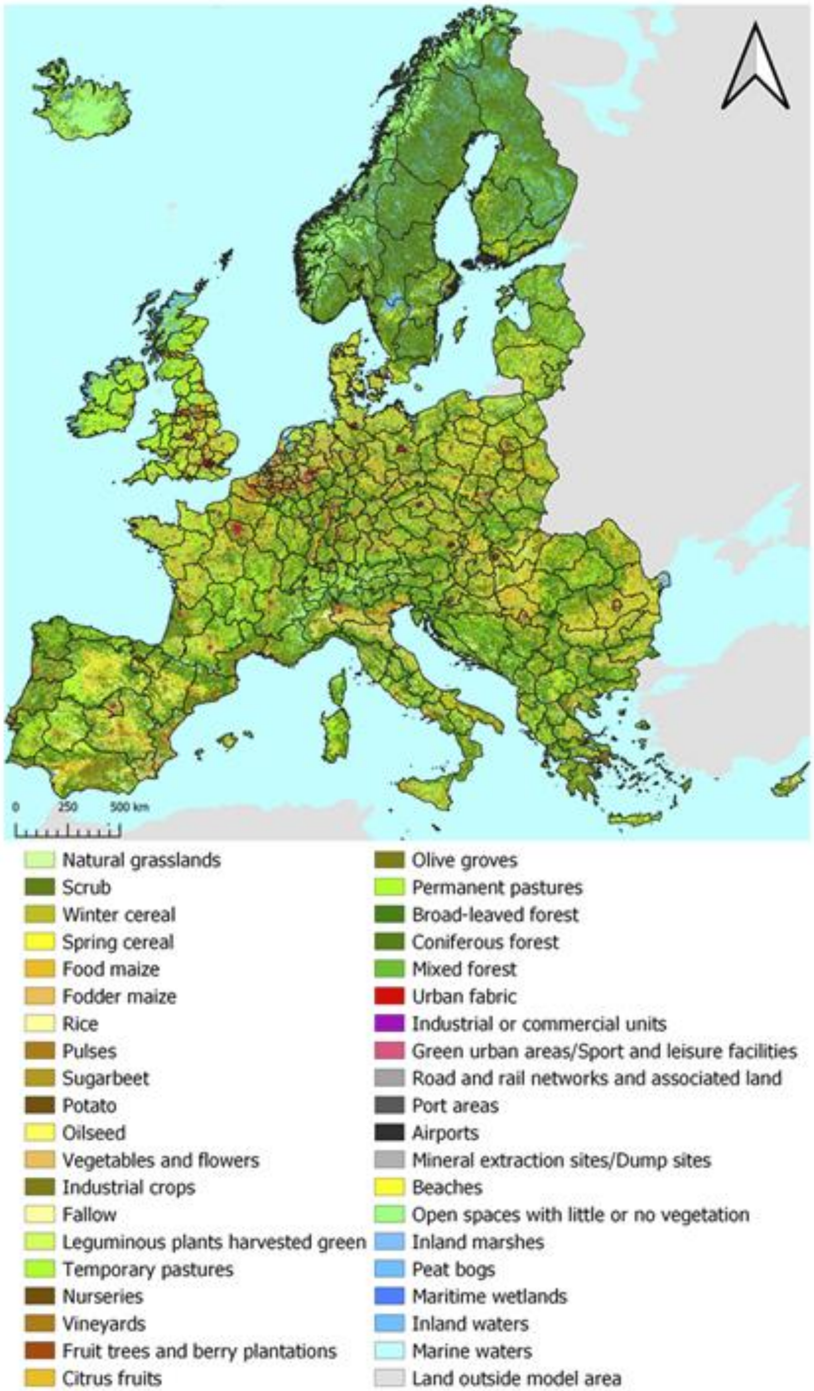


Figure 3.7: SoilCare IAM initial (2018) land use map.

The SoilCare IAM is used in all 3 deliverables of WP6:

- In D6.1 the impact of management practices under current conditions is assessed. For this reason only the PESERA, QUEFTS and MITERRA models are applied here. Focus of the impact assessment in D6.1 has been on:
  - Yield
  - Soil organic carbon
  - Soil erosion
  - Soil nitrogen balance
  - Soil carbon stock
  - Soil nitrogen balance
  - Nitrous oxide (N2O) emission
  - Ammonia (NH3) emission
  - N leaching and runoff
- In D6.2 the impact of management practices on various future conditions is assessed. In doing so, we made use of the AGMEMOD, Metronamica, PESERA and QUEFTS components. Focus of the impact assessment in D6.2 has been on:
  - Domestic use
  - Production
  - Net exports
  - Yield
  - Gross margin
  - Soil carbon stock
  - Soil erosion
- D6.3 makes use of results of the previous two deliverables and as such uses the SoilCare IAM in the way it is applied in those deliverables.

4. Results

This chapter discusses the results of the various activities carried out in the storyline, simulation and policy support process. It follows the 4 stages of the methodology and thus starts with the results of the scoping stage in section 4.1. Next it provides in section 4.2 an overview of the scenario framing which was developed based on the set of interviews conducted early on in the project and the storylines, or qualitative scenarios, development using the framing. This is then followed by their quantification using the SoilCare IAM in section 4.3. The final section (4.4.) describes the policy support obtained from using the scenarios by assessing the robustness of policy actions and discussing what specific actions might be needed to target development in a specific scenario.

4.1. Scoping

Main results of the scoping phase were the selection of stakeholders, the design of the participation throughout the project, and the results of the interviews.

4.1.1. Stakeholder selection

Early in the project, selection criteria for the types of organisations we intended to involve in the participatory activities were developed in collaboration with WP7 and discussed within the wider project team. An overview of all selection criteria is provided in Annex 5. Later on in the project we extended the selection criteria a bit by also involving national level stakeholders, expanding the NGOs a bit by including farm advisory services and interest groups and by inviting farmers. Reasons for doing so were both practical - as by having to organise meetings online we were no longer restricted to stakeholders in the proximity of Brussels, but were able to reach stakeholders from all over Europe - and based on lessons learnt throughout the project. Regarding the latter we increased our focus on farmers and farm advisory services as they provide important insight in the feasibility and relevance of proposed actions.

Here we summarize the main organisation types and list some names of organisations who participated in some or all participatory activities:

- European institutions, e.g., DG ENV, DG AGRI, DG SANTE, JRC
- National institutions, e.g., Dutch Ministry of Infrastructure and Water Management, French Ministry of Ecological Transition, Estonian Ministry of Rural Affairs, Norwegian Agricultural Authority, Flemish government, Swiss, Federal Office for the Environment
- NGOs, e.g., WWF, Birdlife, European Environment Bureau
- Interest groups, e.g., European Landowners Organisation, European Network for Rural Development
- Farmer associations, e.g., Copa Cogeca, International Federation of Organic Agriculture Movements (IFOAM), organization of Brittany's organic farmers, BoerenBond Belgium
- Farm advisory services, e.g., Soil Service of Belgium, Landwirtschaftskammer Rheinland-Pfalz
- Farmers
- Industry, e.g., Unilever, Nestle, SYSTEMIQ, independent consultants
- Key academics

4.1.2. Participatory activities

Throughout the project the aim of the participatory activities has been threefold: for stakeholders to interact, especially those coming from different disciplines; to co-design scenarios and policy options; and to disseminate, discuss and make use of project findings.

To stimulate interaction between stakeholders, but also allow for less vocal stakeholders to express their opinion and ensure stakeholders would have a similar starting point before starting the group activities, we opted for a combination of semi-structured interviews, workshops and a webinar. The aims, process and outcomes of each type of activity are listed below.

Semi-structured interviews

Semi-structured interviews (+/- 20) were organised during the first years of the project, before the first workshop.

The aim of the EU-level interviews was to gain a deeper understanding of the impact of various EU-level policies on agricultural practices, and cropping systems as well as to scope the main uncertainties for the future of Europe and provide input into the development of the Integrated Assessment Model (IAM).

The interviews were conducted in-person, on the phone or through video-conferencing. An overview of the interview script is provided in Annex 6.

The main outcomes included a better understanding of the current policy context and those aspects of policy development that were found important (e.g. combining European-wide policies with a place-based approach), as well as potential or desired policy instruments, a list of key drivers of change (climate change, socio-economic changes such as shifts in diets), and an understanding of quantitative tools used and desired to support the policy impact assessment. Results from the interviews were used in WP7 and to shape the first European-level stakeholder workshop. Based on the interviews the policy-relevant scenario framing was determined along two axes: future challenges for voluntary instruments (aimed to encourage actors to improve their environmental performance to meet and exceed legal obligations) and future challenges for mandatory instruments (standards and practices which oblige actors to perform and behave as defined by law) (see Section 4.2 for more information on the scenario framing).

Workshop: Exploring the future of sustainable agricultural practices in Europe

A *first workshop* was organised in June 2019. This in-person workshop with +/- 20 participants had two main aims:

- Present and obtain feedback on previous work in SoilCare, including the developed SoilCare IAM, primarily focussing on policy options and agricultural practices included and indicators provided.
- Develop qualitative, exploratory scenarios that explore possible future states of Europe that are designed to test the adoption and effectiveness of strategies falling under the categories of voluntary or mandatory instruments.

During the workshop the following activities were organised:

1. Presentation and discussion on the SoilCare IAM
2. Activities to explore the adoption of voluntary and mandatory instruments for sustainable agriculture
3. Activities to explore future drivers and uncertainties impacting on the adoption of instruments
4. Scenario development

To *explore the adoption of voluntary and mandatory instruments (activity 2)*, participants developed a 'meta-plan' for voluntary and mandatory instruments separately. They were asked to answer the question: 'What factors influence the adoption of voluntary/mandatory instruments?' and were each time given a set of post-its to answer this question. They were also asked to indicate on their post-its if the factor was negatively or positively stimulating adoption. Next, stakeholders were asked to stick the post-its on the wall and facilitators clustered and discussed the post-its together with participants. After completing the meta-plan for both voluntary and mandatory instruments, participants were asked to rank the main adoption factors challenging and enabling each type of instrument. For each adoption factor and their impact (+/-) they received three dots/stickers and were asked to place them behind the factor(s) they found most important. This resulted in the following four rankings (factors listed in order of importance):

> *Factors **enabling** the adoption of **voluntary** instruments*: financial incentives, effectiveness of the measure, policy design & communication, social pressure and acceptability, government facilitation & coordination, consistency with existing practices, market signals, and level of organisation and power.

> *Factors **challenging** the adoption of **voluntary** instruments*: financial constraints, lack of knowledge/information, fear of follow-up (legal) actions, paradigm change needed / change in mindset required, uncertainty about the effectiveness, and lack of a legal framework.

*Factors **enabling** the adoption of **mandatory** instruments*: Clear benefits of compliance, support for implementation or transition, simple legislation, strong control and monitoring, level playing field, strong penalties, and no viable alternatives.

*Factors **challenging** the adoption of **mandatory** instruments*: overkill and complexity of regulations, high administrative burden, indirect or invisible benefits, weak monitoring, lack of financial viability, finding agreement on a baseline, lack of public support.

Using the information from activity 2, participants were asked to explore future drivers and uncertainties (activity 3) impacting on the obtained adoption factors. This was done using a 'carousel' format in which the group was split in 3 and groups rotated across stations according to the driver group they were exploring: socio-political drivers, economic and technological drivers and climate and environmental drivers. They hence answered by the end of the activity the following questions:

What are the current and future socio-political drivers that could impact on the adoption of policy instruments for sustainable agriculture?

What are the current and future economic and technological drivers that could impact on the adoption of policy instruments for sustainable agriculture?

What are the current and future climate and environmental drivers that could impact on the adoption of policy instruments for sustainable agriculture?

Results from the previous activity were next used to develop the (qualitative) scenarios. The group was split in two, and each group focused on a specific scenario based on the scenario framing. Due to time constraints during the workshop day, we focused on two scenarios. We selected two scenarios with opposite characteristics to obtain sufficient information to complete the other scenarios after the workshop. During the workshop, participants were asked to develop a timeline, using the following guiding questions:

*In what kind of world would there be **few challenges to voluntary measures** and **significant challenges to mandatory measures**?*

In what kind of world would there be ***significant challenges to voluntary measures*** *and* ***few challenges to mandatory measures****?*

One group started with the first question, the other group with the second, and afterwards groups worked on the alternate scenario. The final activity of the day included a scenario validation exercise with an all-group exercise to discuss any inconsistencies that might be included in the scenarios, make sure the developed scenarios fitted within the framing and were distinct enough and finally that they were extreme, but plausible.

The information from the workshop was next used to develop the storylines as presented in Section 4.2.

Webinar: obtaining feedback on developed storylines

In many scenario studies, scenarios are developed by a limited number of people. To overcome the possible bias resulting from this, we organised a webinar in April 2020 with the aim to give all who are interested in the topic the opportunity to give their input and feedback, and by doing so, contribute to an improved set of scenarios. Furthermore, additional stakeholders were invited to provide their opinion after the webinar through the SoilCare website.

The process we followed was to first extend the list of stakeholders. As we were interested in obtaining feedback from who-ever would be interested in providing this, we sent out invites to selected stakeholders, but also posted the invite on social media and asked relevant organisations to distribute the invitation to their members.

For the webinar itself, we decided to develop little movies, narrated powerpoints, to illustrate the scenarios. These are available on the SoilCare project website: https://www.soilcare-project.eu/resources/policy-scenarios. During the webinar we then presented the project aims and scenario methodology and next asked participants to give feedback on each scenario after watching the scenario movie. Participants were asked to give feedback on the following two questions, but also had the opportunity to provide general comments:

Does the scenario provide a logical sequence of events?

Is the scenario extreme enough, or maybe too extreme?

Participants were asked to respond to the above poll questions with possible responses (very logical, somewhat logical, not very logical, not logical at all) for the first question and (much too extreme, a bit too extreme, right balance, could be a bit more extreme, not extreme enough) for the second question.

After feedback was collected on each scenario individually the webinar concluded with two final questions. The first question was to assess if each scenario in the set of scenarios was sufficiently distinct in its motivating factors and subsequent developments. We therefore asked the following question:

Do you think the scenarios are distinct enough?

Possible answers to this question were: too similar, quite similar, quite distinct and clearly distinct. The second question was meant to assess if the set of scenarios captured the relevant uncertainties for thinking about future developments in European agriculture and making decisions about policies enhancing its sustainability. To obtain this information the following question was asked:

Is the range of scenarios wide enough?

With possible responses including: too limited, rather limited, appropriate range, too wide and much too wide.

Using the feedback from the webinar the storylines were fine-tuned and completed till their final versions as presented in the next section (4.2). The full webinar is available on: https://www.soilcare-project.eu/resources/policy-scenarios

Workshop: Exploring the future of sustainable agricultural practices in Europe

The final workshop was organised as an online event with +/- 30 participants. The aim of the workshop was twofold:

- To present and discuss work carried out in the SoilCare project on sustainable and profitable agricultural pathways for Europe
- To use this information together with the own background and understanding of the participants to identify policy recommendations that are assessed against various socio-economic conditions

And the expected outcomes were:

> To identify policy actions, or actions that can be stimulated by policy, that enhance the adoption of sustainable agricultural practices impacting positively on soil quality and that are:
>
> - Particularly beneficial under particular socio-economic development and thus provide a tailored approach to particular developments
> - Robust across different socio-economic developments as portrayed by the scenarios

During the workshop the following activities were organised:

1. Introduction and setting the scene
2. Presentation and discussion of project results to date (policy work, qualitative scenarios, modelling) as background information for the activities
3. Activity to identify relevant actions for SICS adoption
4. Activity to assess the likely success of actions across scenarios

For the 3rd activity (identify relevant actions for SICS adoption) participants were split into 4 groups, each group working on a specific scenario. They were asked to answer for a specific scenario in a creative and idealistic way the following question:

> What are relevant actions to overcome barriers or encourage enablers to adopt sustainable agricultural practices impacting positively on soil quality?

They were guided in doing so using information obtained in the project on adoption factors, which were classified as policy/institutional, economic, social/cultural, technical, knowledge/information and biophysical (see Annex 7 for the format developed for the exercises). After completing the exercise for one scenario, the groups were asked to add information to a second scenario. At the end of each round participants were asked to rank which activities would be most relevant for the scenario they were focusing on. The highest ranked actions were then used in the final exercise.

The workshop was concluded by assessing if actions found relevant for a specific scenario would also be relevant under some or all other scenarios. For this, a final exercise was developed, where participants (all together) were asked to assess for each highly ranked action from the previous activity the potential for success under all other scenarios. The overarching question for this exercise is formulated as:

> How robust are policy actions under the various scenarios?

The format for this exercise is provided in Annex 8.

The outcomes of this workshop were an identification of best policy actions, of which some are tailored to different contexts and future pathways to target issues in those pathways, while others are robust under a range of pathways.

4.2. Scenario framing and storylines

Based on interviews with stakeholders at European level, policy-relevant scenario framing was determined along two axes, related to different types of policy instruments: future challenges for voluntary instruments (aimed to encourage actors to improve their environmental performance to meet and exceed legal obligations, e.g. subsidies) and future challenges for mandatory instruments (standards and practices which oblige actors to perform and behave as defined by law, e.g. regulations).

We have thus identified types of future worlds where there would be few or significant challenges to either type of instrument. We have done this because understanding what facilitates or inhibits the acceptance and implementation of these instruments may help us to design policies that are well adapted to specific socio-economic contexts or sufficiently robust to be applicable under a range of different scenarios.

Figure 4.1: Overview of the scenario framing together with the scenario titles and their motivating factors.

This framing was subsequently used as the basis for qualitative scenario development in a participatory setting to create narrative storylines for alternative future pathways. The next sections give a short description of each narrative, followed by an overview table indicating the main differences between them. Movies that are created using these narratives are provided on the SoilCare project website: https://soilcare-project.eu/resources/policy-scenarios

4.2.1. Local and sustainable (for the willing and able)

Few challenges to voluntary measures, significant challenges to mandatory measures

With an ever-increasing share of society valuing locally sourced, high-quality produce, the trend towards more sustainably produced food continues. This leads to a large share of the European food being produced sustainably to cater for healthy eating habits of those willing and able to pay for it. This sees a large part of the agricultural sector transform into a more boutique style of farming with a regional focus, and a reduction in food imports from across the world. However, not everyone is able to afford the premium prices of high-quality food, nor interested in changing their lifestyle. Mainstream farmers using conventional practices therefore continue to make up a significant part of the sector.

Production for processed exports remains important and the market also expands for imports from outside Europe, including both imports for products that can be sourced more sustainably outside of Europe, as well as those with lower standards for those unwilling or unable to purchase healthy and sustainable alternatives. Technological developments make agricultural production more traceable across the entire food chain, and this enhanced transparency means buyers increasingly trust what they are paying for. Direct interaction between farmers and individual consumers is facilitated through improved (e-)communication channels. Farm cooperatives are key in supporting social innovation and enhanced communication, including direct marketing and sharing knowledge about sustainable farming practices. The growing awareness of the importance of sustainable practices not just on the environment but also on yield quality and quantity together with the experience on these practices that is built up by an increasing share of farmers leads over time to an increasing demand and production of sustainably produced food.

With groups in society preferring a more locally embedded lifestyle and a large part of the farming community and society placing a high value on wellbeing, heritage and local production, grassroot movements appear across Europe resulting in community members taking responsibility and action for their community by developing food systems that are focused on provenance and quality. This leads to pockets of increased self-sufficiency in food, wood and other rural products across Europe, and significant progress towards a circular economy.

Growing public appreciation for the role of farming and the rural environment triggers a move to the countryside, reinvigorating local communities and motivating good stewardship of the land. But these developments also come with more sprawled residential developments, fragmenting the countryside. Similarly, the desire to become more self-sufficient drives an increase in urban farming.

Local initiatives thrive, partly due to a lack of trust in public institutions to take action. Europe's ambitions for sustainability are rather inward-focused with Member States and regions having a lot of flexibility on the implementation of European policies, empowering land managers to innovate and find their own, locally relevant ways of meeting sustainability targets.

Differences in ability to buy healthy food amplify inequalities in society. Society increasingly values individual freedom, and as a result, there are more choices for consumers from a growing range of production systems that prioritise different preferences, ranging from the preference for cheap food with lower environmental and welfare standards, to organic alternatives and a range of niche markets for local and specialist products that meet health and sustainability preferences.

4.2.2. Under pressure

Few challenges to mandatory measures, significant challenges to voluntary measures

European citizens are increasingly concerned about climate, environmental and health issues, but feel unable to affect change. This leads to numerous protests being organized across Europe to mitigate climate change and produce food more sustainably. With the agricultural sector feeling underappreciated and pushing back with counter-demonstrations, governments are pressured to play a leading role in finding solutions and take action.

After a period of social unrest, it is agreed that food standards can only be met by ensuring more sustainable production. The European Commission is backed by Member States to put forward a set of rules and regulations to ensure the sustainable production of high-quality food, along with a package of support for farmers to comply with them.

However, society has limited capacity to pay for these environmental benefits, and profit margins on food products are under pressure. As a result, many small-scale traditional farmers struggle to meet the regulations while maintaining or increasing their profitability, losing out to large-scale intensive farms that become increasingly dominant. This leads to less diversity in the market and a loss of traditions, but also enables new forms of sustainable production. It offers an opportunity to large-scale farming that can finance and comply with the new more stringent environmental and health standards as well as agile small farms with the ability to adapt.

Technological innovation makes it easier and cheaper to monitor the sustainability of farming practices, enabling the expansion of cross-compliance schemes to a wider range of minimum environmental standards that are required for farmers to receive payment. Larger and more financially healthy farms invest in R&D to meet the new standards, while small farms benefit from well-functioning research and advisory services to find innovative ways to produce sustainably. However, the limited willingness of society to pay for more sustainable products means that the ambition of the agricultural sector rarely goes beyond meeting environmental targets. Still, the demand for European food increases as the new quality standards also apply to imported foods, and overseas producers are increasingly unable to supply products to the specified standards.

Traditional farmers are increasingly being bought out by large enterprises which are abandoning marginal land, leading to a migration from the countryside to cities and less cultural diversity in rural areas. Those remaining in the countryside, who are unable to continue their own farming practice, experience the social and mental health implications of this, as they have lost their purpose and livelihood. New technologies enable an increased intensification with an overall lower need for labour in agriculture, impacting on rural communities as less jobs will be available.

With Europe leading the way in setting the standards for sustainable production, a new generation of young, entrepreneurial and highly educated farmers takes over. Through their modern practices focusing on sustainable and profitable production, over time soil quality together with the other environmental functions increase across Europe while providing a livelihood for those able to keep up.

4.2.3. Race to the bottom

Significant challenges to voluntary measures, significant challenges to mandatory measures

In a context of a failing European sustainability policy, a continuation of existing agricultural practices results in further environmental degradation and impacts on profit margins, due to the costs required for the increasing amounts of inputs needed to maintain production levels. The worsening environmental quality requires quick and more structural solutions to meet the ever-increasing demands from internal and external markets.

Technological innovation is booming in a quest to find more efficient and effective farm practices, with applied research focusing on achieving significant efficiency gains, reducing input costs whilst increasing outputs, and privatized advisory services with a close link to industry facilitating the uptake thereof. However, side effects of these new technologies on the soil and environment are often unknown. As many of the smaller farmers are not able to afford these technologies, the proportion of large industrial farmers increases, as does service provision by contractors.

With the large farms operating with contractors across contiguous blocks of land or even moving to soil-less forms of production, there is a decline of stewardship of the rural areas as the one managing the land is no longer the owner. Heritage and traditions become less important and with the loss of local knowledge built up over decades or even centuries, resilience to deal with unexpected and undesired events is reduced. This alienation from the land also leads to a reduced appreciation of farmers and food production, as the connection between farmers and consumers is distant and agricultural areas are seen as production facilities rather than mixed environments with various uses. There is however scope for rewilding marginal areas where production cannot profitably be pursued.

The focus on quick financial gains implies that decisions are typically driven by a short-term outlook, making it hard to build a case for improvements in soil quality and the environment in general. Politics are heavily impacted by market forces, with large agricultural industries becoming very powerful actors in society and politics. Europe has a strong role in the further globalization of the agricultural sector, which is facilitated by an increase of free trade agreements, and is leading in the export of not just agricultural production, but agricultural technology and machinery as well.

Some groups in European society are able to play a role in new technological developments, either as a producer or a user/consumer of them, and benefit from the economic gains they bring. However, others see few benefits and are unhappy with the direction Europe is headed in, leading to a polarization in society. This division frustrates the ability of governments to pass laws and safeguard agricultural soil quality. Citizen initiatives to change production systems remain small-scale niche solutions for a minority of producers, as small farmers are not organized and corporate value chain actors focus on large volume, low margin food supplies.

4.2.4. Caring and sharing

Few challenges to voluntary measures, few challenges to mandatory measures

Confronted with a series of disasters, including COVID-19, droughts and floods, pests, and animal and plant diseases, there is widespread societal awareness that an urgent change in behaviour is needed to avoid future food shortages. Strong, visionary leaders step up and propose drastic changes that would until recently not have obtained support.

Agriculture, health, environment, and rural development are no longer treated in isolation but considered as integral parts of a resilient food system. There is an increasing understanding and appreciation of the importance of soil for food production and other environmental functions, and soil is widely seen as a public good. Recent disasters that put food supplies at risk lead to a level of solidarity that helped us transition to a more inclusive society with high levels of trust in public institutions. This, together with an increase in communication technologies, also results in a continuous sharing of ideas, good practices and machinery (some government-funded for rural communities), and free advisory services to bridge the gap between research and practice.

This new mindset puts the focus on healthy, sustainably produced food and acknowledges the value of the additional ecosystem services the landscape provides. It comes with a long-term outlook that prioritises climate-resilient agriculture that provides a range of benefits to society. There is widespread awareness and support for investment in more sustainable practices: consumers are willing to spend a larger part of their household budget on food; while a strong government provides financial support to enable this transition and leave no one behind. While local product diversity is burgeoning, reliance on imports is reducing and the associated reduction in food choices is generally accepted by consumers.

With the appreciation of the agricultural environment comes an increased appreciation for living in the countryside, leading to vibrant rural communities that provide a good quality of life. Cities experience a similar change, with a range of urban farming and green initiatives supporting the urban environment and its ecology. Social and technical innovation is high as farmers, citizens and the entire value chain find more sustainable and inclusive ways to produce and consume food. This comes with a sense of belonging and an appreciation for the natural resources the region offers. A strong focus on resilience means that individual choices are restrained through environmental taxes (e.g., carbon tax), with tax revenues being used for environmental benefits and to support those unable to pay more for food.

The change in behaviour extends beyond food production, with fully functional circular economies making sustainable use of resources, and an overall value and care for the environment. Society is more place-based, with less travel for work and holiday, and a lifestyle facilitated by technology (e.g., an increase in remote working, telemedicine etc.). Globalisation is mostly knowledge-based, and imported products have to meet the same social and environmental standards in their production as in Europe.

4.2.5. Scenario overview

Table 4.1: Overview of motivating factors and key drivers per scenario.

Scenario → Characteristics↓	Local and sustainable *for the willing and able*	Under pressure	Race to the bottom	Caring and sharing
Motivating factors	Increasing societal demand for healthy and sustainably produced food, but not everyone is able and willing to join this movement.	Pressure from society and farmers on government to take action on environment and livelihoods, as none feel capable to realise change themselves.	Societal demand for low food prices, coming with overexploitation leading to land degradation and lower production or higher costs for inputs.	Confrontation with disasters triggers society to rapid and drastic change, resulting in a holistic resilience approach with a vast appreciation for society and environment.
Economy	Increased market demand for healthy and sustainably produced food. The role of mainstream agriculture is reduced.	Limited financial capacity in society. Small profit margins for farmers. Less diversity in the market due to regulations.	Focus on short-term financial gains. Exports of technology and cheap food facilitated by free trade agreements.	Fully functioning circular economies, making sustainable use of resources. Globalisation is mostly knowledge-based.
Farm practice	Boutique and mainstream farming co-exist.	Sustainable intensification on large farms and agile small farms.	High production, large-scale farming.	Wide range of sustainable farm practices.
Technology and knowledge transfer	Increased traceability. Improved communication technology to facilitate use of best practices. Grassroot initiatives and cooperatives drive improved sustainability.	R&D is focused on monitoring and meeting regulations, but little ambition to go beyond. Likewise, advisory services focus on providing advice on meeting requirements.	High-tech focused on efficiency, side effects often uncertain. Funding for R&D through the agricultural sector including wealthy farmers. Privatised advisory services.	High-tech options for all farm sizes to complement traditional practices or develop new ones. Freely available advisory services bridge the gap between research and practice.
Socio-cultural	Individual capabilities, desires and decisions are shaping our future. Mix of different lifestyles and farming practices. Increased self-sufficiency at local and regional level.	Loss of traditions. Social implications for small-scale farms going out of business. Increase of young entrepreneurial, highly educated farmers who can make the switch to new practices.	The one managing the land is not the owner. Loss of traditions and knowledge impact on resilience. Distant connection between farmers and consumers.	Focus on well-being, solidarity and a sense of belonging. A large part of the household budget is spent on food, especially regional produce.
Politics and institutions	Lack of trust in public institutions to take action. Fewer	Strong government regulation with associated high costs.	Agricultural producers become powerful actors in society and	Governments and individuals working together to establish

	EU policies, decision power at national, regional and local level.	Strong EU, protective of its citizens. Imports required at EU standards.	politics. EU lacks funding and trust to make a difference.	change. Strong EU with financial capabilities due to increased taxes.
Land use and environment	Urban to rural migration, with a competition for land in the countryside. Mixed landscapes.	Rural to urban migration. Mixed uses and land management practices within large farms.	Rural to urban migration. Decline of mosaic landscapes and abandonment of marginal lands.	Current rural depopulation trends stopped. Multi-functionality of landscapes.

4.3. Scenario quantification

4.3.1. Linking storylines to modelling

To facilitate the scenario quantification, we first listed those scenario drivers for which inputs could be simulated by the models. We distinguish five main driver groups that can be used for the quantification of the scenarios:

Consumption: changes in diets, e.g., shifts from meat to a more plant-based diet. Linked to model drivers *per capita meat consumption, per capita cereals consumption,* and *per capita pulses consumption*.

Imports and exports: higher shares of import or exports for all or some commodities. Linked to drivers *imports and exports*.

Farm practices: more or less sustainable practices based on the share of organic production and the use of SICS (cover crops, mulching, minimum tillage, compaction alleviation or combinations thereof). Linked to the drivers *area share of organic production* and *agricultural practice*.

Population and GDP: For all scenarios the same population and GDP projections are used. Until 2030 use is made from the population and GDP projections from AGMEMOD. Beyond 2030 (till 2050) use is made of the ESPON project ET2050 - Territorial Scenarios and Visions for Europe (https://www.espon.eu/programme/projects/espon-2013/applied-research /et2050-territorial-scenarios-and-visions-europe).

Climate change: For all scenarios use is made of the RCP 4.5 scenario. It would also be possible to run the simulations with the RCP 8.5 scenario as these climate projections are also included in the SoilCare IAM (see Annex 2).

From the storylines and the overview table in the previous section (4.2) *Clues* are taken and *Consequences* defined (see Section 2.3) and these are mapped to model inputs linked to the driver groups provided above, and for these model inputs a quantification is provided. A summary of this quantification is provided in Table 4.2.

In the following section scenario results are presented. We first provide results on the differences in domestic use across the scenarios, followed by the production and the net exports. Next, we discuss the expected changes in yield per hectare and the related cost-benefit expectations of applying the SICS. The quantification concludes with the modelled sustainability impacts on soil organic carbon and erosion.

Because the AGMEMOD model simulates developments till 2030 we only include information till 2030 for those indicators on which AGMEMOD provides information. We have extrapolated trends when needed till 2050 as discussed in Section 3.1.1.

Detailed parameterizations of model parameters are explained in the respective model annexes (Annexes 2, 3 and 10).

In the next sections, often reference is made to the scenarios using the following abbreviations: Race to the Bottom (RttB); Under Pressure (UP); Local & Sustainable, for the willing and able (LS); Caring & Sharing (CS).

Table 4.2: Overview table model inputs based on scenario drivers.

DRIVER		Race to the bottom	Under Pressure	Local & Sustainable	Caring & Sharing
Per capita meat consumption	**Assumption**	**BAU (business-as-usual)** No additional willingness to consume more sustainably	**Decrease (-)** Decrease in meat consumption due to government intervention	**Decrease (-)** Part of citizens largely acknowledge the need to decrease meat consumption, part is unwilling or unable. Differences between regions/countries within EU	**Decrease (--)** There is a widely accepted need to decrease meat consumption in order to consume more sustainably
	Quantification	Continuation of current trend	Up to 2030: -1.25%/year (for the entire EU)	Up to 2030: -1.5%/year for countries with meat consumption equal to or above average and -1%/year for countries with meat consumption below average	Up to 2030: -2%/year (for the entire EU)
Per capita cereals consumption	**Assumption**	**BAU (business-as-usual)**	To compensate for decreased meat consumption		
	Quantification	Continuation of current trend	Up to 2030: +0.24%/year (for the entire EU)	Up to 2030: +0.29%/year for countries with meat consumption equal to or above average and +0.19%/year for countries with meat consumption below average	Up to 2030: +0.38%/year (for the entire EU)
Per capita pulses consumption	**Assumption**	**BAU (business-as-usual)**	To compensate for decreased meat consumption		
	Quantification	Continuation of current trend	Up to 2030: +0.28%/year (for the entire EU)	Up to 2030: +0.34%/year for countries with meat consumption >= average and +0.23%/year for countries with meat consumption < average	Up to 2030: +0.45%/year (for the entire EU)
Imports	**Assumption**	**BAU (business-as-usual)** Well-functioning market mechanism without changes in trade	**BAU (business-as-usual)** No changes in imports as demand of citizens for local food products is not translated in government action.	**Decrease (-)** Part of citizens express a demand for local food products, while others do not care about origin.	**Decrease (--)** There is a wide-spread demand for local food products.
	Quantification	Continuation of current trend	Continuation of current trend	25% reduction of net imports at EU-level divided over net importing countries based on their share in EU production amongst net importing countries	50% reduction of net imports at EU-level divided over net importing countries based on their share in EU production amongst net importing countries

Exports	**Assumption**	**BAU (business-as-usual)** Well-functioning market mechanism without changes in trade	**Decrease (-)** Decrease in net exports to allow for decrease in UAA instead of filling up area for export. Additionally, decrease in EU net exports due to government intervention	**Decrease (--)** Decrease in net exports to allow for decrease in UAA instead of filling up area for export. Additionally, decrease in EU net exports due to demand for more local food products and decrease in globalization by part of citizens.	**Decrease (---)** Decrease in net exports to allow for decrease in UAA instead of filling up area for export. Additionally, decrease in EU net exports due to demand for more local food products and decrease in globalization by a considerable share of citizens.
	Quantification	Continuation of current trend	Net EU exports are allowed to grow with maximally 2 times de yield trend. Additionally, net EU exports decrease with 20% divided over net exporting countries based on their share in net EU exports.	Net EU exports are allowed to grow with maximally 2 times de yield trend. Additionally, net EU exports decrease with 40% divided over net exporting countries based on their share in net EU exports.	Net EU exports are allowed to grow with maximally 2 times de yield trend. Additionally, net EU exports decrease with 60% divided over net exporting countries based on their share in net EU exports.
Area share of organic production	**Assumption**	**BAU (business-as-usual)**	**Increase (+)** The EU goal of 25% of EU area under organic production is reached but no further efforts are done to increase this value.	**Increase (+)** Demand of part of citizens for more sustainable production is translated into increases in the area share of organic production at EU-level but increases differ across countries.	**Increase (++)** Demand for more sustainable production is translated into considerable increases in the area share of organic production.
	Quantification	Continuation of current trends	Increase of share under organic production to 25% in 2030 over entire EU	Increase of share under organic production to 25% in 2030 at EU level. Increases per country differ, based on current shares in EU area under organic production.	Increase in organic production to 25%, 30% or 35% in 2030, depending on current area share under organic production
Agricultural practice	**Assumption**	**Low sustainability approach**	**Medium sustainability approach everywhere. Same level of SICS application everywhere**	**Mix of low, medium and high sustainability approach reflecting farmer and consumer preferences**	**High sustainability approach**
	Quantification	No application of SICS	All farmers apply 1 SICS: 25% mulching, 25% cover crops, 25% minimum tillage, 25% compaction alleviation	1/3 of farmers applies a low sustainability approach, 1/3 a medium sustainability approach and 1/3 a high sustainability approach	All farmers apply a combination of SICS. 50% applies cover crops, minimum tillage and compaction reduction and 50% mulching, minimum tillage and compaction reduction

4.3.2. Model results

Domestic use

In table 4.3 changes in domestic use are shown for each scenario in 2030 compared to 2020, expressed in percentage points for EU-14 and EU-N13. EU-14 are the countries that accessed the EU before 2004, EU-N13 the countries that accessed the EU after 2004. This division is used as previous studies often found differences in economic activities between both due to their history and difference in timing of EU accession. In appendix 9 an overview is shown of the countries belonging to both groups. The arrows in table 4.3 indicate an increase (arrow up, green), status quo (arrow right, orange) or decrease (arrow down, red) in domestic use, while the colour of each cell reflects a gradient of increases from red (10th percentile of results), to orange (50th percentile of results) and green (90th percentile of results). As such, arrows show the direction of change while colors reflect the magnitude of change. Hence, green cells reflect the highest increases in domestic use compared to 2020, while red cells reflect the highest decreases.

Domestic use encompasses all types of use including food, feed, seed, etc., while the exact categories differ between commodities. Generally, domestic use increases over time, especially in EU-N13, at moderate levels, in all scenarios. This reflects population increases over time with generally higher increases expected for EU-N13, while additional mechanisms play a role in the remaining scenarios. Specifically, domestic use of pulses increases most in EU-14 in the UP, LS and CS scenarios, in line with the assumptions of decreasing meat consumption and increasing consumption of replacers including pulses. Differences over scenarios are explained in more detail below.

On the other hand, the increase in domestic use of pulses is smaller in EU-N13 (compared to EU-14), while highest increases for this region are present for oilseeds, apples and maize, in all scenarios. Furthermore, domestic use of cereals decreases for EU-14 in the CS scenario while they increase considerably in EU-N13, although changes remain moderate. Domestic use of potatoes decreases in the RttB, UP and LS scenarios in both regions, while they remain more or less the same (increase below 1%) in the CS scenario.

In conclusion, generally increases in domestic use are observed in line with increasing population, especially in EU-N13. Nevertheless, differences are present between commodities and between EU-14 and EU-N13. In particular, domestic use of potato decreases in all scenarios except for the CS scenario, while use of cereals and maize decreases in the CS scenario in EU-14 only. Pulses increase most in domestic use in EU-14, followed by tomatoes, while increases are higher in EU-N13 for cereals, maize, oilseeds and apples.

Table 4.3: Changes in domestic use expressed in percentage points for each of the four scenarios modelled in 2030 compared to 2020, in EU-14 and EU-N13. Arrows indicate an increase (green), status quo (orange) or decrease (red) in production, while the color of a cell reflects a gradient with increases from red (10th percentile) to orange (50th percentile) and green (90th percentile). RttB: Race to the bottom; UP: Under pressure; LS: Local and sustainable; CS: Caring and sharing.

	EU-14				EU-N13			
Commodity	% change 2020 - RttB2030	% change 2020 - UP2030	% change 2020 - LS2030	% change 2020 - CS2030	% change 2020 - RttB2030	% change 2020 - UP2030	% change 2020 - LS2030	% change 2020 - CS2030
Cereals	2,18	0,51	0,44	-0,52	5,54	4,91	5,37	5,3
Maize	2,13	-0,19	0	-1,87	8,98	7,54	7,7	7,04
Rice	2,07	1,66	2,75	4,03	0	0	0	0
Pulses	6,36	9,57	9,98	15,48	1,38	1,76	1,69	2
Sugarbeet	3,67	3,94	4	3,99	0,75	0,93	0,85	1,39
Potato	-1,98	-1,04	-0,57	0,95	-2,7	-2,01	-1,26	0,28
Oilseeds	3,63	3,1	3,54	3,88	9,01	8,63	9,92	10,58
Tomato	7,86	7,86	7,86	7,86	1,99	1,99	1,99	1,99
Citrus fruits	0,48	0,48	0,48	0,48	3,36	3,36	3,36	3,36
Apples	2,94	2,94	2,94	2,94	10,67	10,67	10,67	10,67

In figure 4.2, the relative difference in domestic use in 2030 of the major EU commodities is shown for the UP, LS and CS scenarios relative to the RttB scenario for both EU-14 (blue) and EU-N13. Generally, domestic use of cereals and maize is lower in the UP, LS and CS scenarios compared to the RttB scenario, while higher values are generally observed for rice, pulses, sugar beet, potato and oilseeds. This decrease is probably due to decreases in meat consumption and hence associated fodder requirements. While compensation of decreased meat consumption was assumed to be partly through increases in cereals consumption, the net decrease indicates that these values were lower than decreases due to meat consumption reduction. On the other hand, increases in domestic use compared to the RttB scenario are larger for pulses in the CS scenario in EU-14 as compensation for decreased meat consumption, while this effect was considerably smaller in EU-N13. Also, domestic use of potatoes was higher in the UP, LS and CS scenarios compared to the RttB scenario, although domestic use still decreased over time in the UP and LS scenarios as shown in table 4.3.

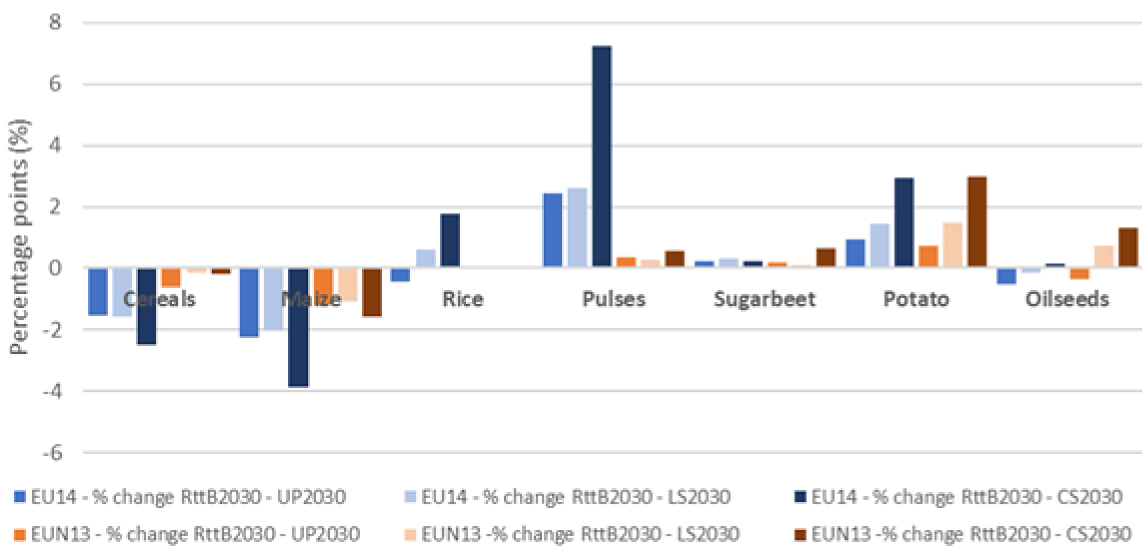


Figure 4.2: Percentage point differences in domestic use of the major EU commodities in 2030 for the UP, LS and CS scenarios relative to the RttB scenario for EU-14 (blue) and EU-N13 (orange).

Production

Similar to the presentation of the results on domestic use, table 4.4 shows changes in production of major EU agricultural commodities in 2030 for the four scenarios modelled compared to 2020. Interpretation of colors and symbols is identical to the previous section and will not be described in detail here.

Overall, production increases for most commodities in both EU-14 and EU-N13 in all scenarios. Nevertheless, increases are generally highest in the CS scenario, especially for EU-14. While the mechanism driving production increases in the RttB scenario are increasing yields, the generally higher (or less negative) values in the LS and CS scenario stem from decreases in imports implemented, compensated by an increase in area and production to meet demand. Largest increases in production are observed for the commodities maize, pulses and oilseeds over all scenarios, citrus fruits in the LS and CS scenarios and rice for the LS and CS scenario in EU-N13. Especially for citrus fruits, large increases are found due to decreases in net imports, as net imports at EU level are considerable for citrus fruits. Nevertheless, only a limited number of countries in the EU are producers of citrus fruits and hence this effect is relatively small in absolute values.

Largest decreases in production are generally observed for potatoes, especially in EU-N13, with highest values in the RttB scenario. Similarly, decreases in production are present for tomatoes, but only in EU-14 that is a net importer of tomatoes, while EU-N13 is a net-exporter. Comparing EU-14 and EU-N13, the largest differences seem present for cereals, pulses, potatoes, and tomatoes. While cereals production generally increases moderately in EU-14, increases are larger especially in the RttB scenario in EU-N13, while cereals production in EU-N13 decreases in the CS scenario. On the other hand, increases in pulses production are considerably higher in EU-14 while limited in EU-N13. Furthermore, decreases in potato production are higher in EU-N13 while moderate in EU-14.

In conclusion, production generally increases over time in EU-14 and EU-N13 for most commodities, while decreases are found for potato in both regions and tomato for EU-14. These decreases in production (as well as in domestic use observed above) probably originate from the decreasing trend observed over time in some EU countries due to changing diets and globalization. Nevertheless, the AGMEMOD model does only include country-specific submodels for the potato sector while they are not yet integrated at EU-level. Therefore, uncertainties for the potato sector remain present in the AGMEMOD model that might impact results. Additionally, increases are generally largest for the CS scenario and the commodities maize, pulses and oilseeds, but differences are present between EU-14 and EU-N13 generally linked to differences in being respectively net importer or exporter of commodities.

Table 4.4: Changes in production expressed in percentage points for each of the four scenarios modelled in 2030 compared to 2020, in EU-14 and EU-N13. Arrows indicate an increase (green), status quo (orange) or decrease (red) in production, while the color of a cell reflects a gradient with increases from red (10th

percentile) to orange (50th percentile) and green (90th percentile).

Commodity	EU-14				EU-N13			
	% change 2020 - RttB2030	% change 2020 - UP2030	% change 2020 - LS2030	% change 2020 - CS2030	% change 2020 - RttB2030	% change 2020 - UP2030	% change 2020 - LS2030	% change 2020 - CS2030
Cereals	4,87	2,79	2,94	4,2	13,69	7,01	2,76	-4,79
Maize	15,16	19,31	25,7	31,75	21,29	21,42	25,2	26,7
Rice	0,55	0,99	8,06	16,09	10,74	7,37	19,64	30,17
Pulses	12,51	14,44	16,91	31,96	0,97	1,13	2,07	3,42
Sugarbeet	2,54	2,93	4,38	5,87	0,48	0,8	1,94	4,1
Potato	-4,39	-1,74	-0,6	3,75	-17,91	-14,85	-12,47	-3,52
Oilseeds	18,47	18,45	54,34	82,31	14,01	12,51	20,71	28,8
Tomato	-3,84	-4,16	-4,16	-4,16	6	6	6	6
Citrus fruits	0	0	52,43	104,85	0	0	69,9	139,8
Apples	1,71	1,71	1,71	1,71	0,9	0,9	0,9	0,9

Analogous to the description in the previous section on domestic use, figure 4.3 shows the relative difference in production in 2030 of the major EU commodities for the UP, LS and CS scenarios relative to the RttB scenario for both EU-14 (blue) and EU-N13 (orange). Generally, production increases in the LS and CS scenarios compared to the RttB scenario with largest increases in the CS scenario due to assumptions made on more local (European) production and less trade (imports). Differences between the RttB scenario and the UP scenario are generally relatively small. Moreover, these observations are mostly similar in EU-14 and EU-N13, although differences are present in the magnitude of changes, for example for maize and oilseeds with largest increases in EU-14. Nevertheless, production decreases in both EU-14 and EU-N13 for cereals in all scenarios, although decreases are largest in EU-N13. As both regions are net cereal exporters, and cereals take up the largest share in area and production, this is the result of the decrease in exports implemented in the scenarios compared to RttB.

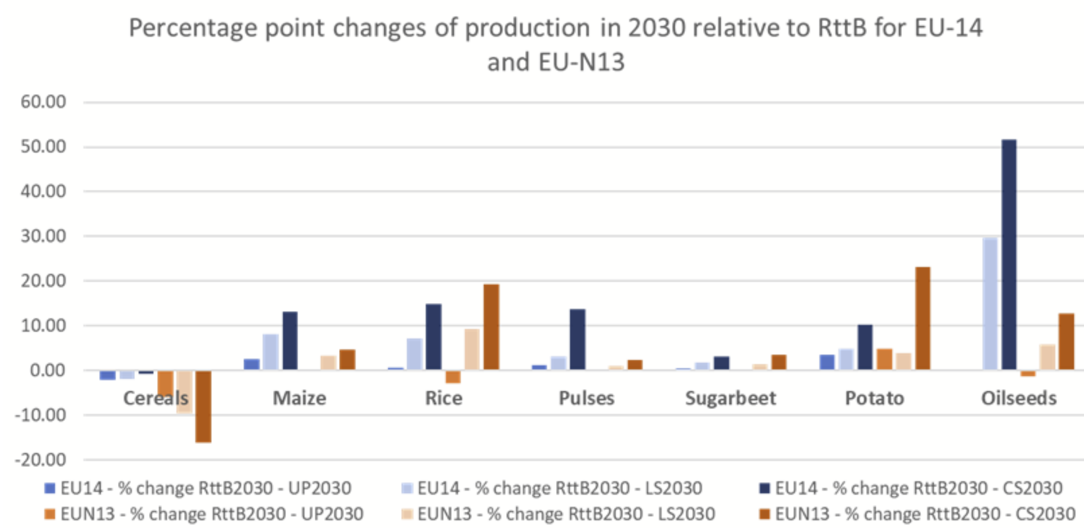


Figure 4.3: Percentage point differences in production of the major EU commodities in 2030 for the UP, LS and CS scenarios relative to the RttB scenario for EU-14 (blue) and EU-N13 (orange).

Net exports

Changes over time in net exports or imports in 2030 relative to 2020 are shown for each scenario and agricultural commodity in Table 4.5, expressed in percentage points. For this, net exports were calculated for EU-14 and EU-N13 for 2020 and each of the scenarios, resulting in each region being a net exporter or importer for each agricultural commodity as shown in the table. Similar to the approach used for data representation above, increases are indicated by green arrows pointing upwards, status quo by orange arrows pointing right and decreases by red arrows pointing downwards. However, these changes reflect increasing/decreasing net exports (grey background) or net imports (white background), depending on the commodity and region. Generally, values decrease more over time in EU-14 compared to EU-N13 and in the LS and CS scenarios in both regions, the latter in line with the scenario assumptions. The former is likely due to EU-14 trading relatively larger volumes compared to EU-N13. Furthermore, values are relatively very high, ranging from increases with a factor of almost 3 observed for cereals exports in the RttB scenario for EU-14 to decreases of more than a factor 3 for tomato imports in EU-14 in all scenarios. This is probably the result of AGMEMOD using trade to keep the balance in production and consumption, but might reflect relatively limited numbers in absolute values (compared to e.g., production) as is for example the case for tomatoes, for which EU-14 is a (slightly) net exporter in 2020 but becomes a (slightly) net importer in 2030 in all scenarios.

Table 4.5: Changes in net exports or imports expressed in percentage points for each of the four scenarios modelled in 2030 compared to 2020, in EU-14 and EU-N13. Arrows indicate an increase (green), status quo (orange) or decrease (red) in production, while the color of a cell reflects a gradient with increases from red (10th percentile) to orange (50th percentile) and green (90th percentile.

	EU-14					EU-N13				
Commodity	***Net exporter or importer***	**% change 2020 - RttB2030**	**% change 2020 - UP2030**	**% change 2020 - LS2030**	**% change 2020 - CS2030**	***Net exporter or importer***	**% change 2020 - RttB2030**	**% change 2020 - UP2030**	**% change 2020 - LS2030**	**% change 2020 - CS2030**
Cereals	Exporter	198,63	68,7	-2,36	-79,46	Exporter	27,22	7,32	-1,17	-21,3
Maize	Importer	-1,88	-9,65	-19,13	-29,78	Exporter	36,89	38,43	51,25	61,76
Rice	Exporter	-96,24	-88,87	-70,11	-53,81	Importer	-1,46	-1,01	-3,08	-1,58
Pulses	I (E in CS)	-66,86	-6,54	-22,1	-177,27	Importer	2,77	4,03	-0,72	-5,33
Sugarbeet	Importer	0,62	0,62	-33,52	-67,69	Importer	8,04	8,04	-6,33	-20,65
Potato	Exporter	22,42	7,01	0,95	-23,18	Importer	62,22	42,92	43,71	18,25
Oilseeds	Importer	-1,01	-0,74	-19,83	-35,73	Exporter	21,96	15,67	38,57	78,68
Tomato	Importer	-258,5	-258,5	-258,5	-258,5	Exporter	-5,92	-5,92	-5,92	-5,92
Citrus fruits	Importer	0,48	0,48	-25,36	-51,2	Importer	2,78	2,78	-6,76	-16,29
Apples	Importer	6,29	6,29	6,29	6,29	Exporter	2,79	2,79	2,79	2,79

Table 4.6 shows differences expressed in percentage points between net exports or imports in 2030 for the UP, LS and CS scenarios compared to the RttB scenario, with arrows and colours identical as above. As observed in the table above, values of net imports and exports are generally lower compared to the RttB scenario, with overall increasing magnitudes towards the CS scenario, except for rice in EU-14 with large increase in percentage points but reflecting lower decreases in exports and relatively low numbers in absolute values. Furthermore, net exports of pulses increases in the UP and LS scenario compared to the RttB scenario in EU-14, while net exports of maize and oilseeds increase in the LS and CS scenarios compared to the RttB scenario for EU-N13. These increases are likely to originate from AGMEMOD's assumptions of balancing through trade.

Table 4.6: Changes in net exports or imports expressed in percentage points in 2030 for the UP, LS and CS scenarios compared to the RttB scenario, in EU-14 and EU-N13. Arrows indicate an increase (green), status quo (orange) or decrease (red) in production, while the color of a cell reflects a gradient with increases from

red (10th percentile) to orange (50th percentile) and green (90th percentile).

	EU-14				EU-N13			
Commodity	***Net exporter or importer***	**% change RttB2030 - UP2030**	**% change RttB2030 - LS2030**	**% change RttB2030 - CS2030**	***Net exporter or importer***	**% change RttB2030 - UP2030**	**% change RttB2030 - LS2030**	**% change RttB2030 - CS2030**
Cereals	Exporter	-43,51	-67,3	-93,12	Exporter	-15,64	-22,31	-38,14
Maize	Importer	-7,91	-17,58	-28,43	Exporter	1,13	10,49	18,17
Rice	Exporter	195,78	694,26	1127,4	Importer	0,46	-1,64	-0,12
Pulses	I (E in CS)	181,98	135,05	-333,15	Importer	1,22	-3,4	-7,88
Sugarbeet	Importer	0	-33,93	-67,89	Importer	0	-13,3	-26,56
Potato	Exporter	-12,59	-17,54	-37,25	Importer	-11,89	-11,41	-27,1
Oilseeds	Importer	0,28	-19,01	-35,07	Exporter	-5,15	13,62	46,51
Tomato	Importer	0	0	0	Exporter	0	0	0
Citrus fruits	Importer	0	-25,72	-51,43	Importer	0	-9,28	-18,56
Apples	Importer	0	0	0	Exporter	0	0	0

Relative shares domestic use, production and net trade at country level

This section provides a graphical representation of the domestic use, production and net trade at country level, for each of the largest commodities: cereals, maize and oilseeds.

Figure 4.4 shows the relative shares of production, domestic use, and net exports or net imports, of *cereals* for each country in the reference year 2020, and for the RttB scenario and the CS scenario in 2030. These scenarios were selected for country-specific representation of results as generally differences in values in the region-specific analysis were largest for these scenarios. Furthermore, they represent the two most extreme scenarios (i.e. high challenges for mandatory and voluntary instruments versus low challenges for mandatory and voluntary instruments respectively). The size of the pie chart reflects the sum of absolute values over production, domestic use and net exports or imports. As such, they indicate the size of the role of a country in the cereals market. Germany, France, Spain and Poland are largest cereals net traders with Spain being a net importer while Germany, Poland and especially France are net exporters. Generally, Southern and most Western European countries are net cereal importers while Central, Eastern and Northern European countries are net exporters. In the RttB scenario, relative shares generally do not change a lot, except for slight increases in the share of net exports, especially for the largest net exporters Germany and France. This is in line with expectation as the RttB scenario mostly assumes a business-as-usual practice. However, differences in relative shares seem to be more pronounced and in the opposite direction in 2030 between the RttB and CS scenarios. Specifically, a decrease in the share of net exports is observed for France, Romania, Bulgaria and Latvia. Given the trade limitations in this scenario, this is also in line with expectation.

Similar to the previous figure, figure 4.5 shows the relative shares of production, domestic use and net exports or net imports of *maize* for each country in the reference year 2020, and for the RttB scenario and the CS scenario in 2030. Generally, France, Romania, Spain, Italy and Hungary play the largest roles in the maize market with Spain and Italy being net importers while France, Romania and Hungary are net exporters. Broadly, Western and Southern Europe are net maize importers, except for France, while eastern Europe are net exporters, in the reference year and both scenarios. Northern Europe contributes to the maize market to a very limited extent.

Again, over time in the RttB scenario, changes in relative shares are relatively small, in line with expectations. On the other hand, some differences can be observed between relative shares in 2030 for the CS scenario compared to the RttB scenario 2030. In particular, relative shares of net imports decrease in Spain, Italy, Greece, France and especially Poland, compensated by an increase in the relative share of production to ensure a balance between supply and demand.

In figure 4.6, shares of production, domestic use and net trade are shown for oilseeds in the reference year 2020, and the RttB scenario and the CS scenario in 2030. Western Europe, Central Europe and southern Europe are generally net importers of oilseeds, while eastern Europe is generally a net exporter, except for Poland. The contribution of the Baltic countries and Denmark to the oilseeds market is relatively small. Production of oilseeds takes up a considerable share mainly in France, Italy and to a lower extent in Germany in Western and Southern Europe, while other countries in these regions mainly rely on imports. On the other hand, production takes up a considerable share in most Eastern European countries and to a lower extent in Northern European countries such as Denmark.

Over time in the RttB scenario, differences are relatively small except for an increase in the relative share of production in Italy and Germany in 2030. On the other hand, these changes are more pronounced in the CS scenario. Specifically, production shares increase considerably in Germany, Italy, France, Spain, Austria, Greece and Poland that are net importers in 2020, due to implemented decreases in oilseeds imports. As a consequence, some of the countries that were net importers in 2020 (i.e. those with a relatively small share of net imports) become net exporters in 2030 in the CS scenario such as France, Italy and Poland.

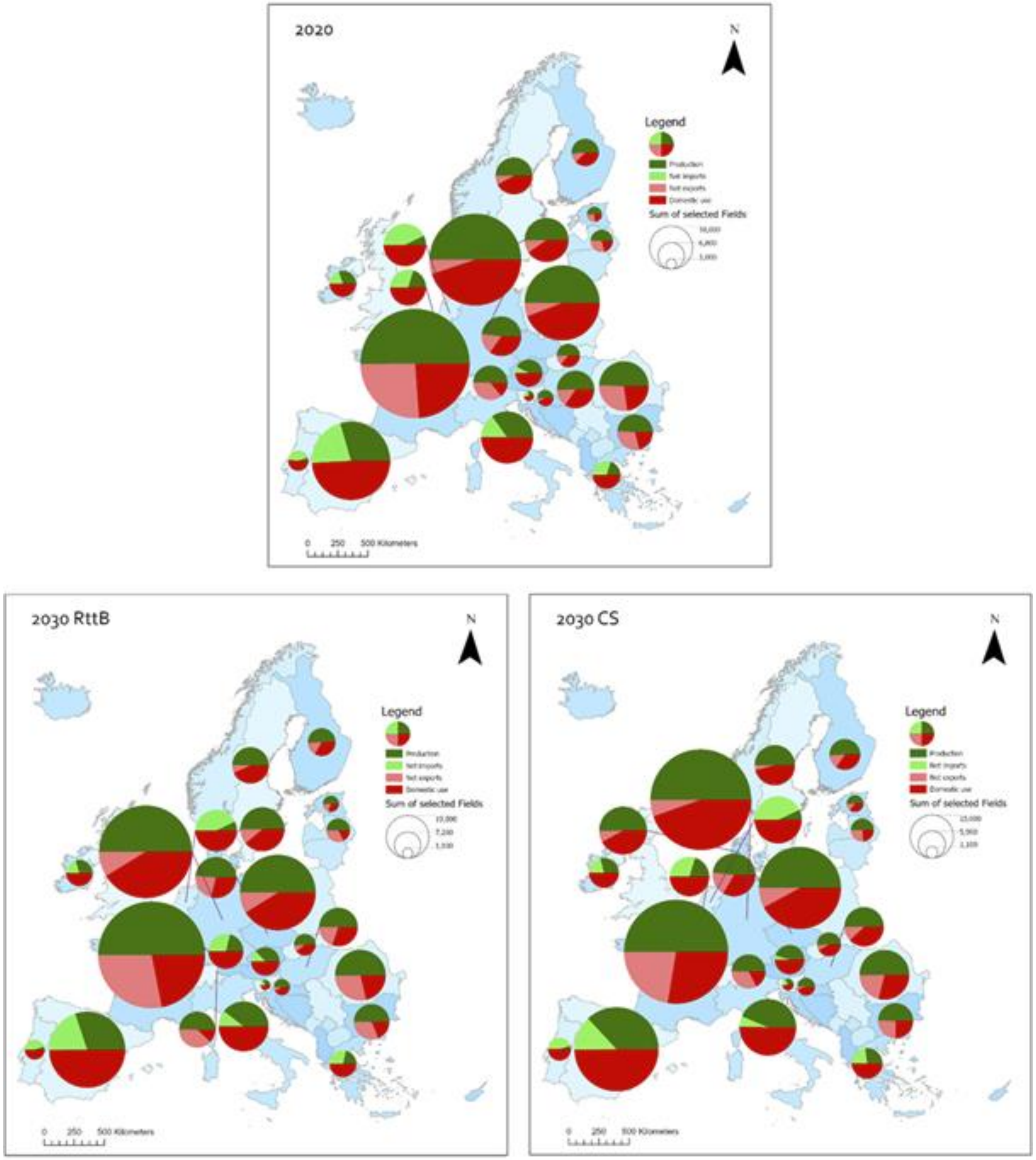


Figure 4.4: Relative shares of production, domestic use and net exports or net imports of cereals for each country in the reference year 2020, the RttB scenario and the CS scenario. Sizes of the pie chart reflect absolute values for the sum of absolute values over production, domestic use, and net exports/imports.

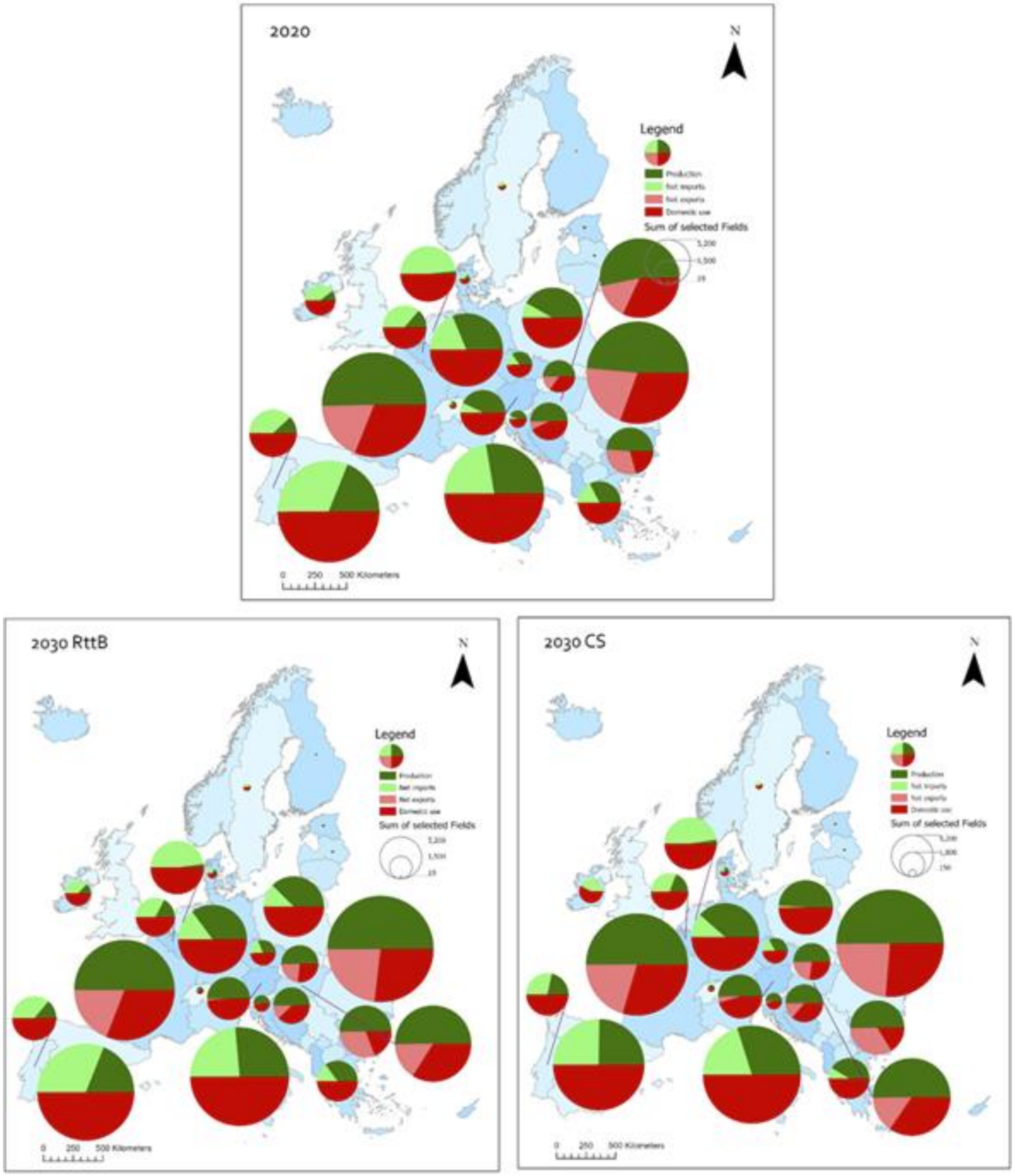


Figure 4.5: Relative shares of production, domestic use, and net exports/net imports for maize per country for the reference year 2020, the RttB scenario and the CS scenario. Sizes of the pie chart reflect absolute values for the sum of absolute values over production, domestic use, and net exports/imports.

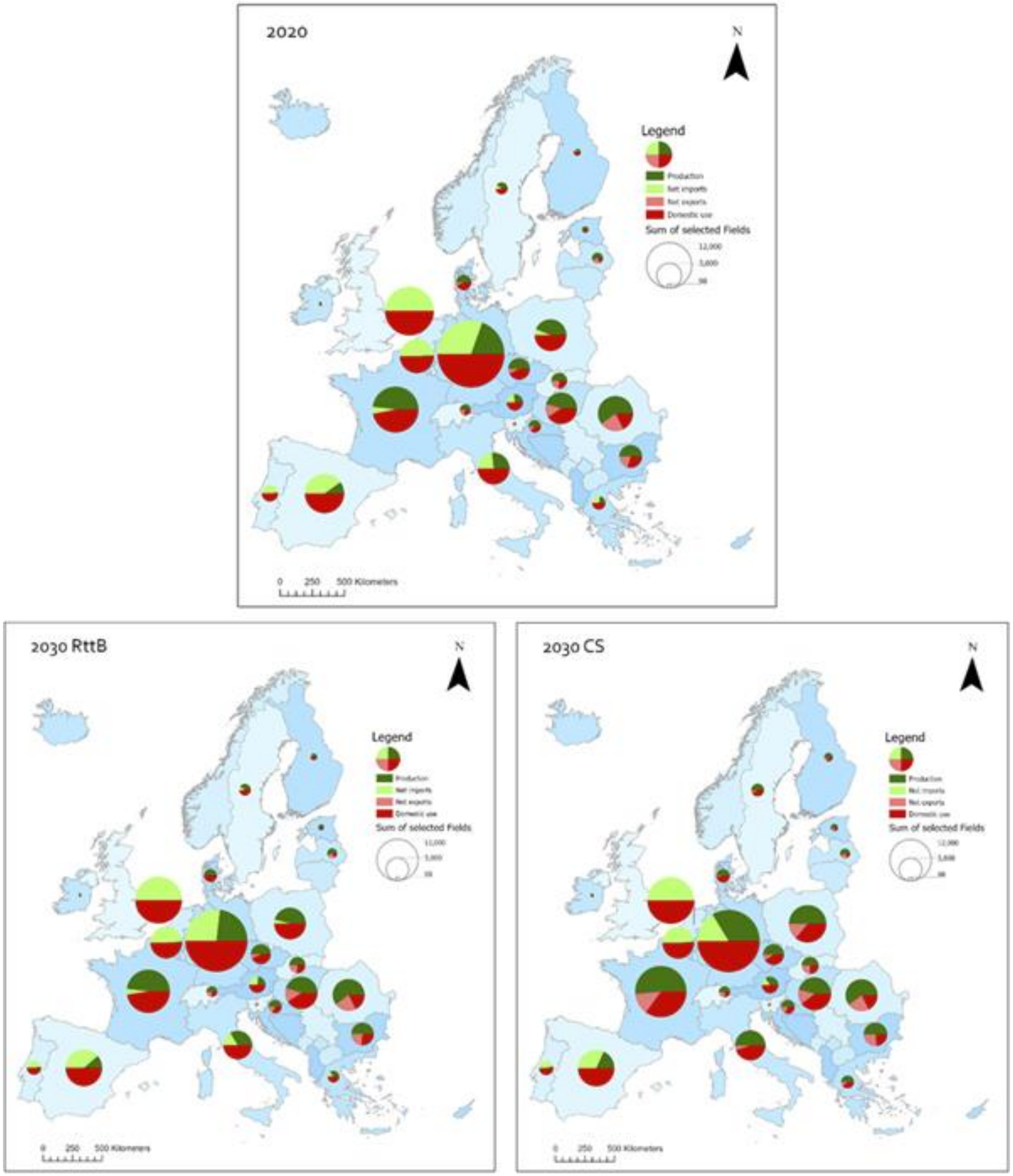


Figure 4.6: Relative shares of production, domestic use, and net exports/net imports for oilseeds per country for the reference year 2020, the RttB scenario and the CS scenario. Sizes of the pie chart reflect absolute values for the sum of absolute values over production, domestic use, and net exports/imports.

Yield impacts

Figure 4.7 shows the relative yield impact for lumped crops by 2030 in different scenarios relative to 2020. Changes in yields relate to changes in environmental conditions, technological changes, and the impact of SICS. In the RttB scenario, no SICS are applied. Most of Western Europe presents stable yields, and most of Eastern Europe presents modest to moderate yield increases, particularly in the Baltic States and Bulgaria, which is mainly due to technological change (Figure 4.8), which also occurs in the Netherlands. In Southeastern Europe, technological changes are the largest but impacts on yield are partially offset by negative impacts of environmental change, while in the Baltic States and Finland, more limited technological change is aided by positive effects of environmental change.

In the UP scenario, yields in most of France, parts of Germany and Ireland are stable, while areas of strong increases in yield are occurring in Italy, Southeastern Europe, the Baltic states and Finland, England, and - to lesser extent- Iberia (Figure 4.7). Figure 4.8 explains that these trends are underpinned by negative technological effects (e.g., large-scale changes to organic production) in the former case and the impact of SICS generally. The relative impact of SICS is highest in Western Europe, where technological change effects are less prevalent (expansion of organic agriculture is less as initial values are higher, while yield trends are generally more stable too as current technology is further advanced).

In the LS and CS scenarios, the higher application of SICS leads to further yield increases. The spatial patterns differ somewhat: in the LS scenario France, and, to a lesser extent Switzerland, Austria, Iceland and parts of Germany perform the poorest (Figure 4.7). Figure 4.8 shows that this is mostly due to modest yield impacts of SICS applied in these regions. In the CS scenario, overall, yield increases are the strongest, but lagging in France, Poland, Ireland and especially Germany. The CS scenario leads to negative technological impacts (most importantly the largest increase of organic production across the scenarios) in these areas that put a dent in the positive effect by higher rates of SICS application.

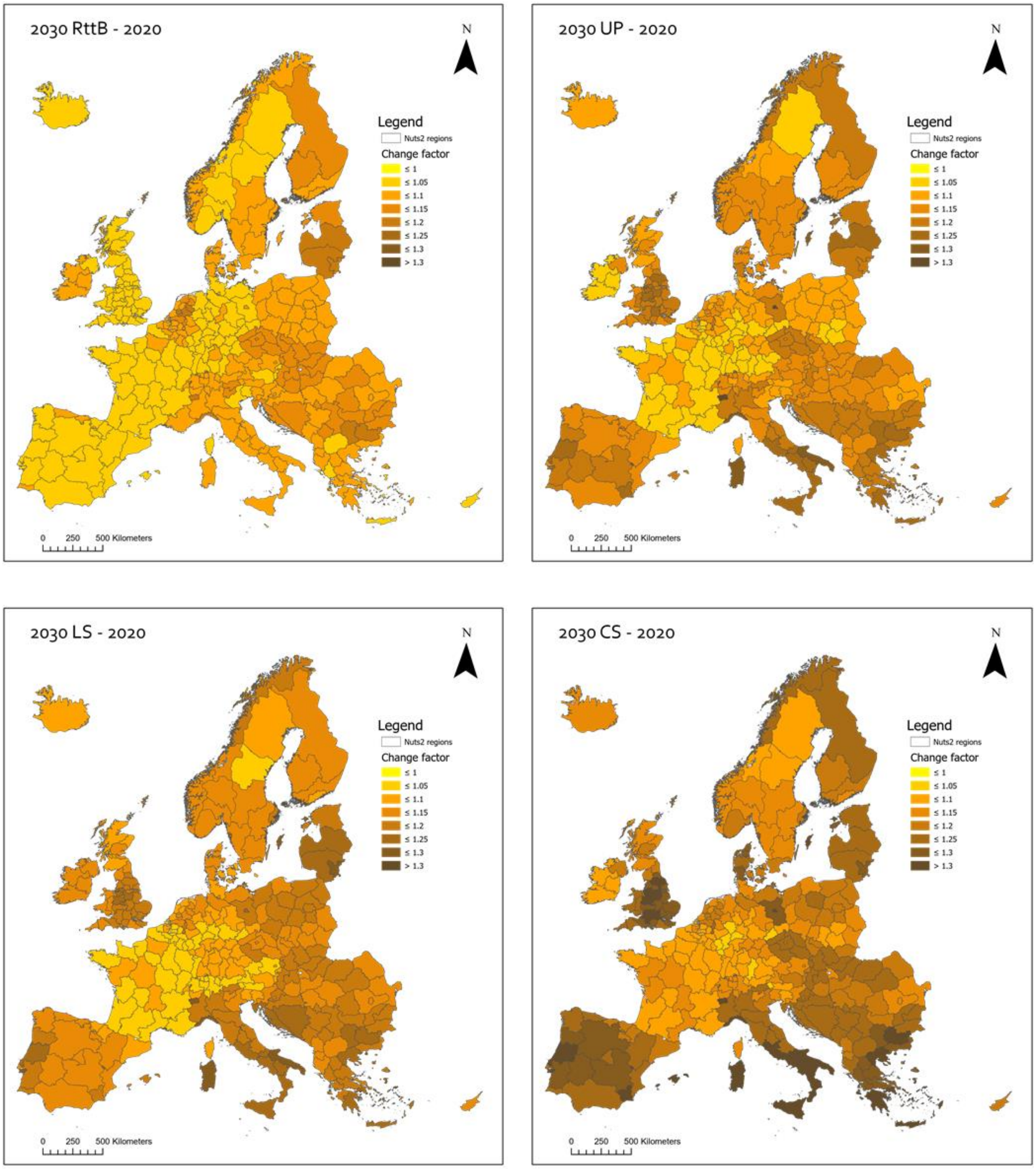


Figure 4.7: Yield increases in 2030 relative to 2020 in the four scenarios modelled, averaged over crop types

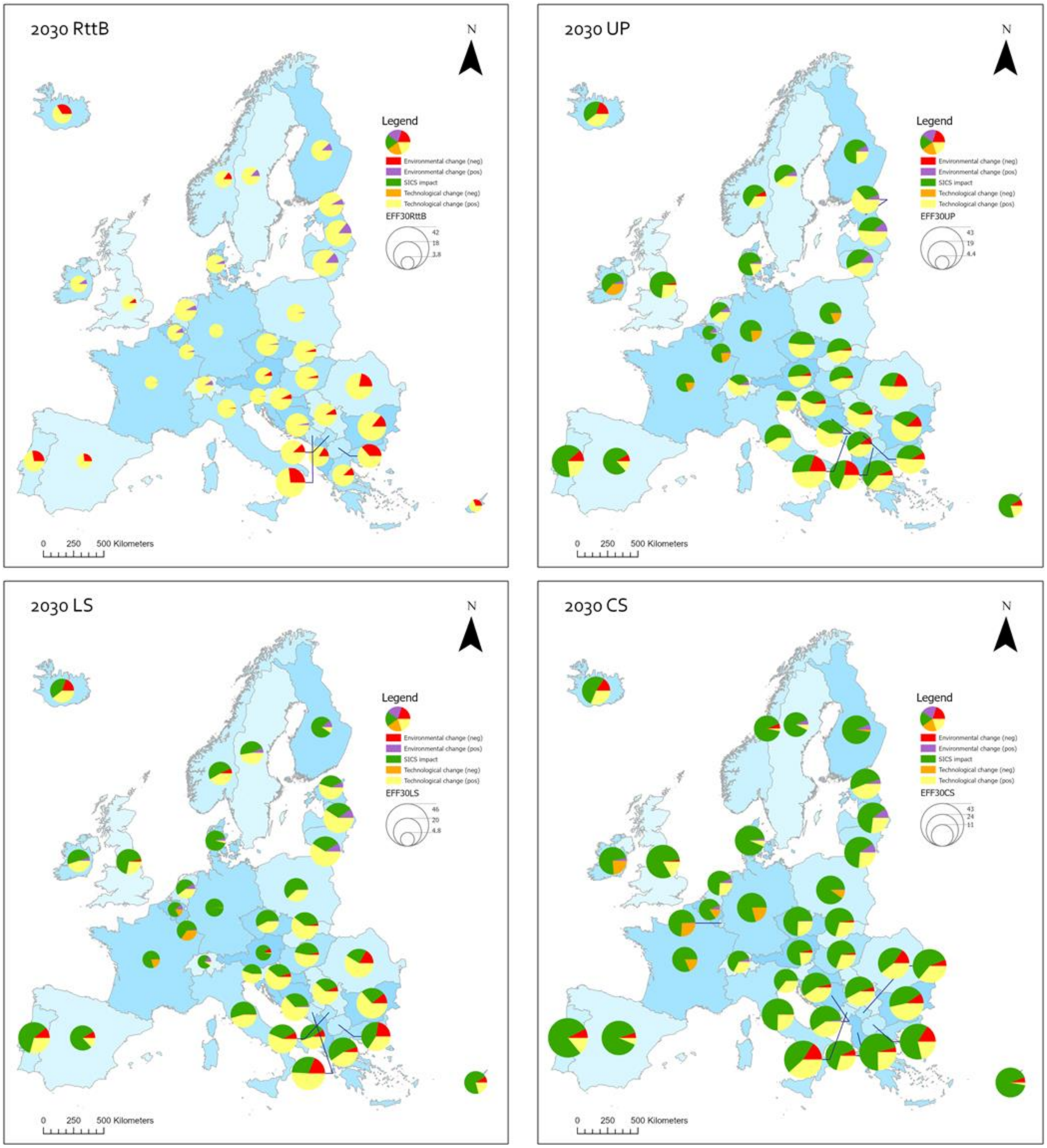


Figure 4.8: Factors explaining the yield increases 2020-2030 in the four scenarios modelled. Absolute impacts are shown to weigh negative and positive impacts equally.

Figure 4.9 shows yield changes between 2020 and 2050 for the different scenarios. In the RttB scenario yields in Cyprus, Iceland, North Macedonia, and much of Spain remain stable, while yields in the Baltic States, the Netherlands, Bosnia Herzegovina and Bulgaria increase most. Technological trends, that are positive everywhere, are offset by negative environmental change effects in the countries where yields are stable. In the UP scenario, declining yields (i.e. values <1) are notable in Ireland and parts of France and Germany. Negative technological trends are causing this trend. The impact of SICS is not sufficient to counter this effect. In many countries on the Balkan, the impact of SICS roughly compensates for the negative environmental change impact. Yet, yields increase here due to technological change (Figure 4.10). Substantial yield increases are also notable in Italy, Portugal and England when comparing to the RttB scenario.

In the LS scenario, yields in Austria, Belgium, France, Germany, Luxemburg, Slovenia and Switzerland as well as Cyprus and Iceland do not change much between 2020 and 2050, while other countries feature more substantial yield increases. Poland and Slovakia perform especially well in this scenario (Figure 4.9). Technological change is the main determinant of these trends. In the CS scenario, larger effects of SICS implementation stimulate yields in many countries, particularly in Czech Republic, England, Greece, Portugal and Spain, whereas these countries perform comparatively less well in the other scenarios. The impact of SICS is the main driver of this performance. In contrast, Central and Southern Germany features stable or decreasing yields; negative technological impact here prevails over SICS impact (Figure 4.10).

Figure 4.11 shows which scenario leads to the best yield outcome per NUTS-2 region. In the majority of the regions, the CS scenario leads to the highest yields. In terms of SICS impact, this is as expected, as yield impacts of all SICS are either neutral or positive, but not negative in the model outputs. However, the LS scenario also covers quite a number of NUTS-2 regions, more so in 2050 than in 2030. These regions will have stronger technological development in this scenario than under the CS scenario. In a number of regions, including Belgium, Luxemburg, parts of France, Germany and the Netherlands, and southern Finland, yields are highest under the RttB scenario in 2050. Also here, other scenarios may lead to negative technological impacts (most importantly the large increase of organic production across the scenarios) that are not sufficiently compensated by SICS impact on yield. Finally, a number of regions in Austria and Switzerland perform best under the UP scenario.

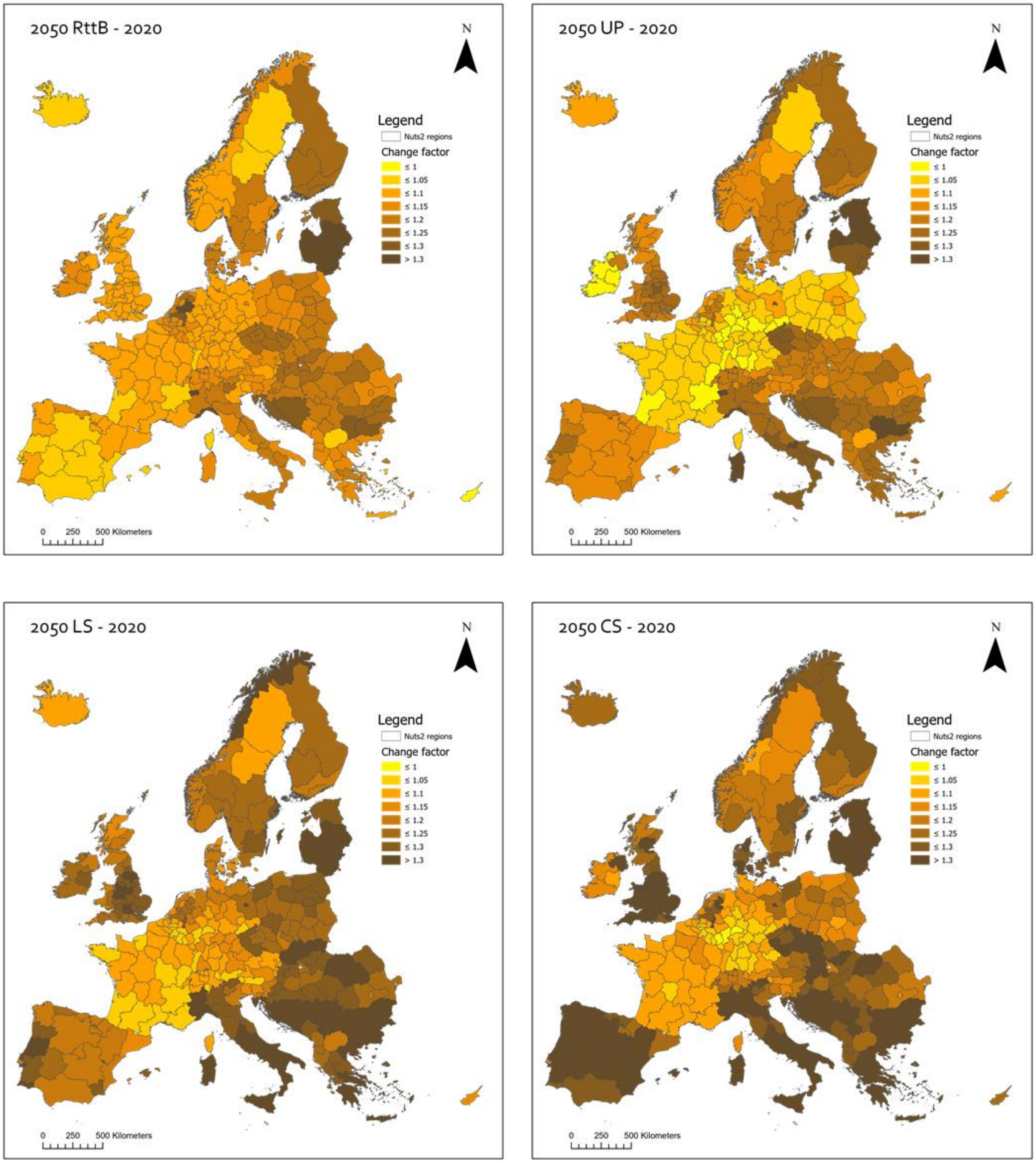


Figure 4.9: Yield increases in 2050 relative to 2020 in the four scenarios modelled.

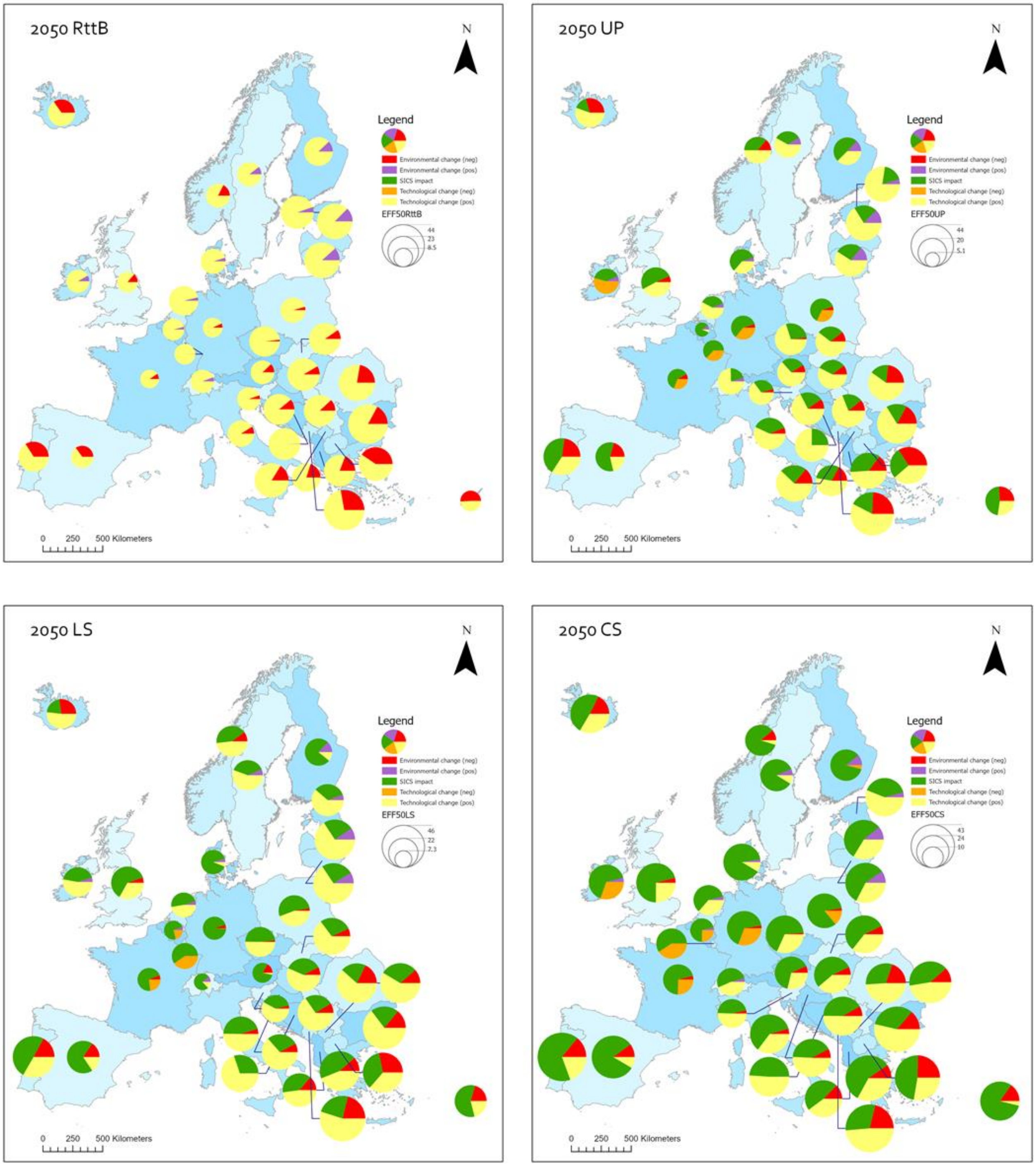


Figure 4.10: Factors explaining the yield increases 2020-2030 in the four scenarios modelled. Absolute impacts are shown to weigh negative and positive impacts equally.

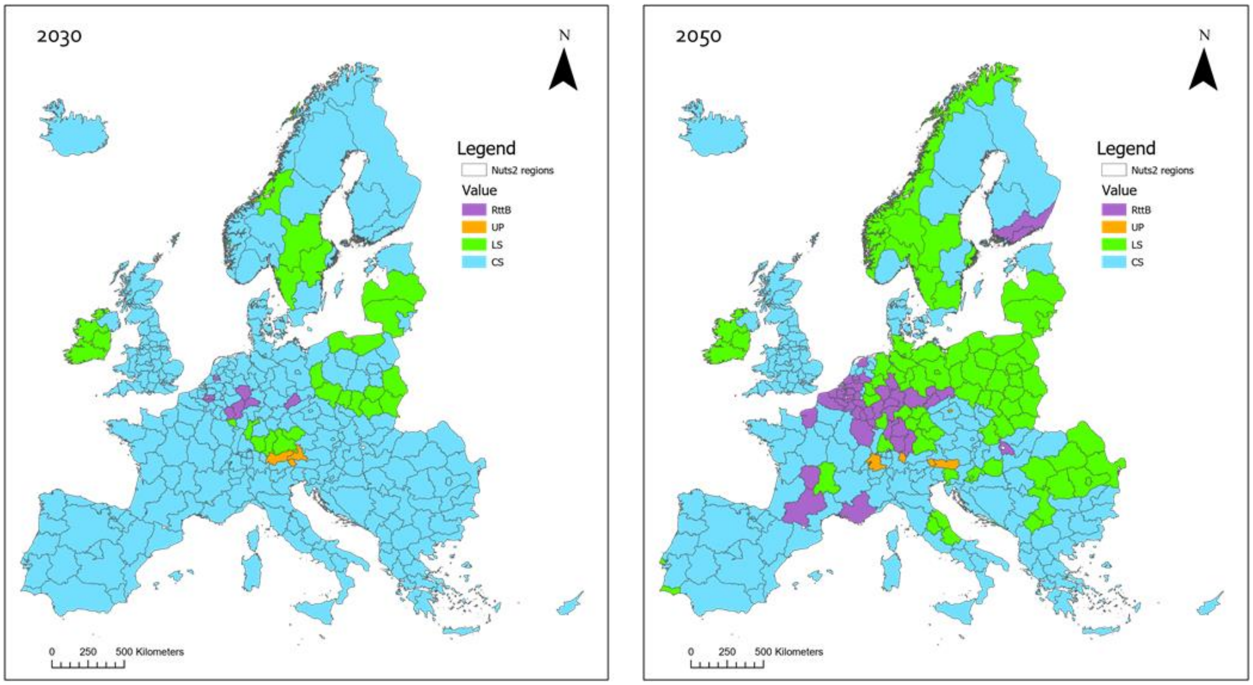


Figure 4.11: Scenarios leading to the highest yield increase in 2030 and 2050.

Cost-benefit analysis

A gross-margin analysis was performed to understand where and under which circumstances the uptake of SICS is generating a profit for farmers as a bottom-line level assessment excluding several co-benefits of SICS mentioned by stakeholders. Factors influencing the profitability are:

- Implementation costs. The costs of different SICS were reviewed and stylised for this scenario exercise (see Annex 10): implementation of cover crops and compaction reduction measures were set at a net extra cost of €75 per ha, mulching at a net extra cost of €250 per ha, while minimum tillage was assumed to lead to a cost saving of €50 per ha. The costs of combinations of SICS were assumed to be equal to those of the most expensive component.
- Yield increase. The yield increase relative to a no measures (RttB) scenario was taken as a basis to assess the production benefit. Factors of environmental change (different between 2030 and 2050) and technological change (different between scenarios and

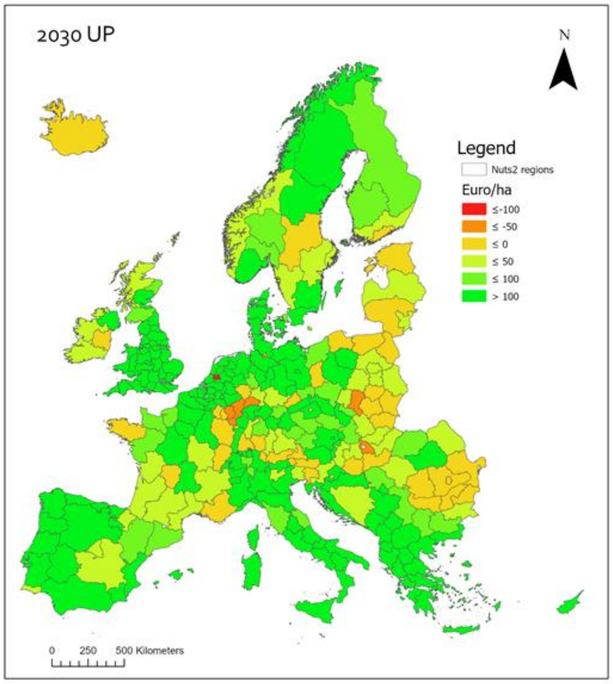
years) were taken into account. Yield increase was modelled with the PESERA/QUEFTS model.

- Crop price. Crop price developments under the various scenarios were obtained from the AGMEMOD model simulations.

Figure 4.12 shows the results of the gross-margin analysis for different scenarios and years. The yield differences vary between years, leading to different outcomes between 2030 and 2050. Under the UP scenario, implementation of SICS is limited to applications of single measures, i.e., limiting costs of SICS implementation. As yield increases are observed, profitability is highest under crops and in locations with highest comparative prices. For most NUTS-2 regions, SICS implementation under the UP scenario leads to a positive result. Exceptions are in particular areas of Germany and Switzerland, but also southern France, eastern Poland and parts of Austria, Hungary and Slovenia where a negative gross margin is obtained.

Under the LS scenario, a higher number of NUTS-2 regions shows profitability of SICS implementation. A mixed uptake of SICS in this scenario leads to intermediate costs and yield impacts, translating into larger gross margins in many areas. Notable areas where SICS implementation is not profitable under the LS scenario are parts of Austria, Germany and Switzerland, southern France and southern Finland, and Estonia. Negative gross margins result when yield impact of SICS is limited or prices against which to value yield increases are low.

Although the CS scenario leads to highest yield impact (Figures 4.9 and 4.11 in the section on Crop yield), Figure 4.12 shows that the gross margin of SICS uptake under this scenario is negative in many NUTS-2 regions. The most important factor contributing to this is the high implementation costs assumed when combinations of measures are implemented (either 75 or 250 Euro per ha). SICS implementation is especially at a loss in southern France, Switzerland, Austria and parts of Germany, Poland, Romania and Sweden. SICS implementation under the CS scenario is mostly profitable in southern Europe, England and Denmark, and a patchwork of areas from Northern France to Western Poland. Despite sustainability being high on the agenda in the CS scenario, financial support will likely be needed to enhance uptake of SICS.


2030 UP
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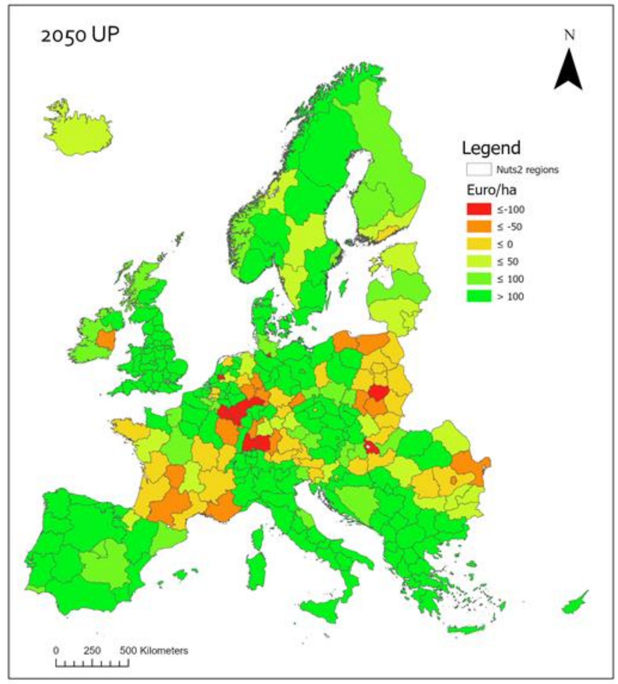
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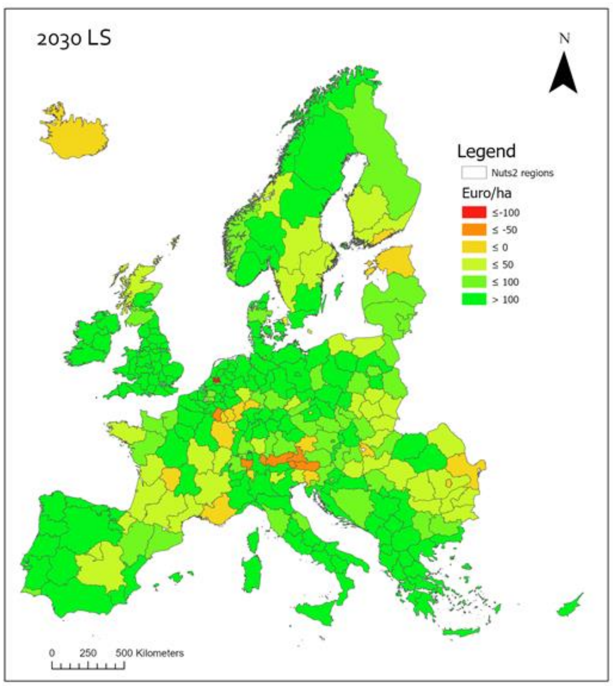
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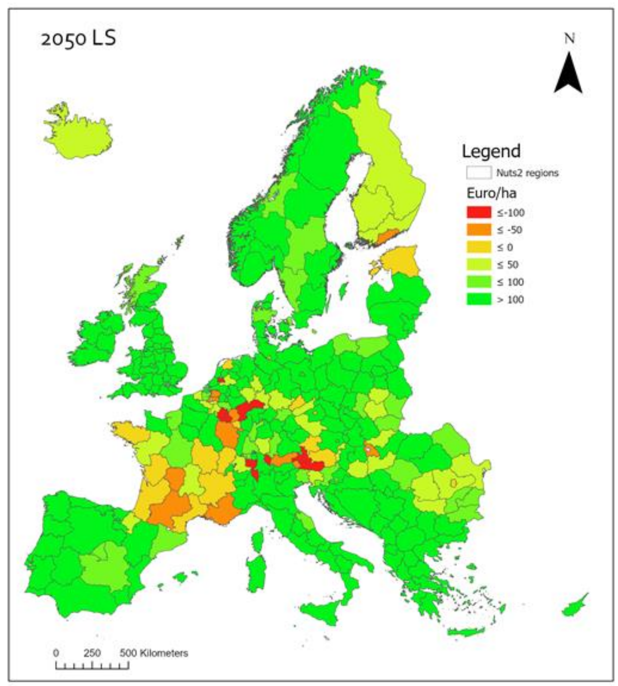
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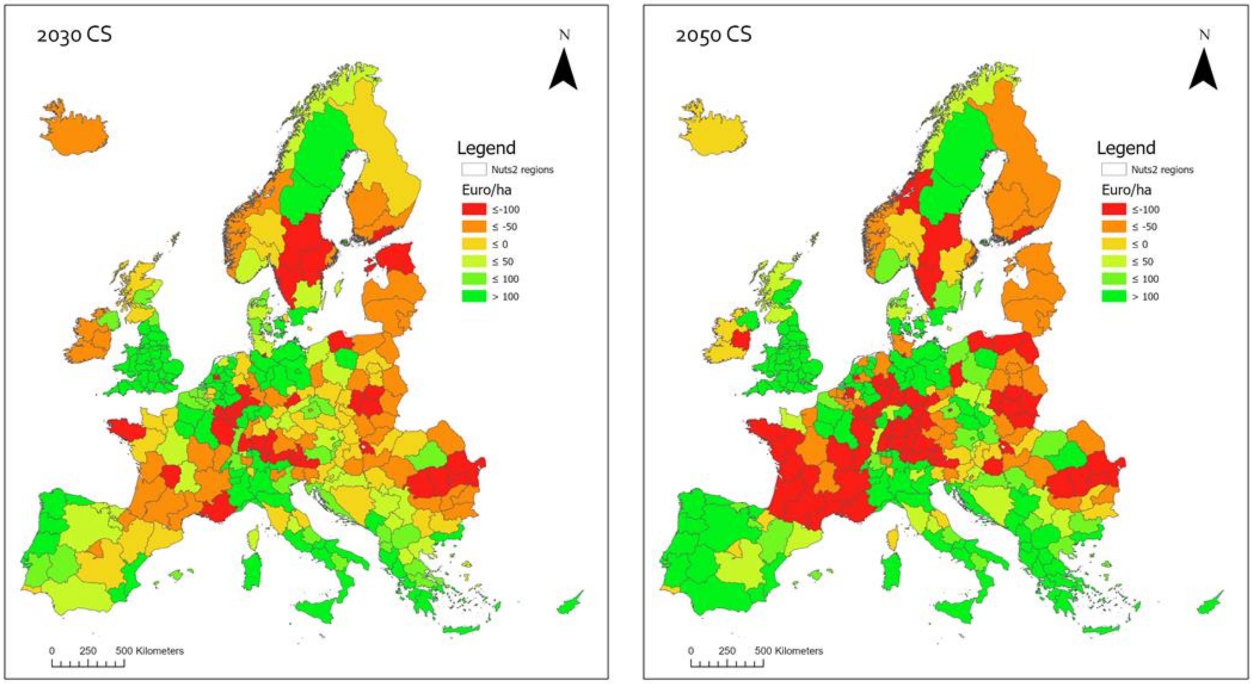

Figure 4.12: Gross-margin analysis of SICS implementation per NUTS-2 region under the UP, LS and CS scenarios against a reference baseline of the RttB scenario.

Figure 4.13 presents the scenarios under which the highest gross margin is obtained. Contrary to yield impacts (Figure 4.11), where the CS scenario dominated the maps, highest gross margins are most frequently obtained under the LS scenario. An intermediate level of investment in SICS apparently leads to sufficient yield impact to outperform other scenarios, although specific technological changes in this scenario may also contribute to this good relative performance. Notwithstanding, in some areas SICS do not seem to add value financially (e.g. Iceland, Estonia and several regions in France, Germany, Austria and Romania) and the RttB scenario obtains the best outcome. Furthermore, areas of England, Belgium, Denmark, Switzerland, Finland, Czech Republic, Hungary and others perform best under the UP scenario.

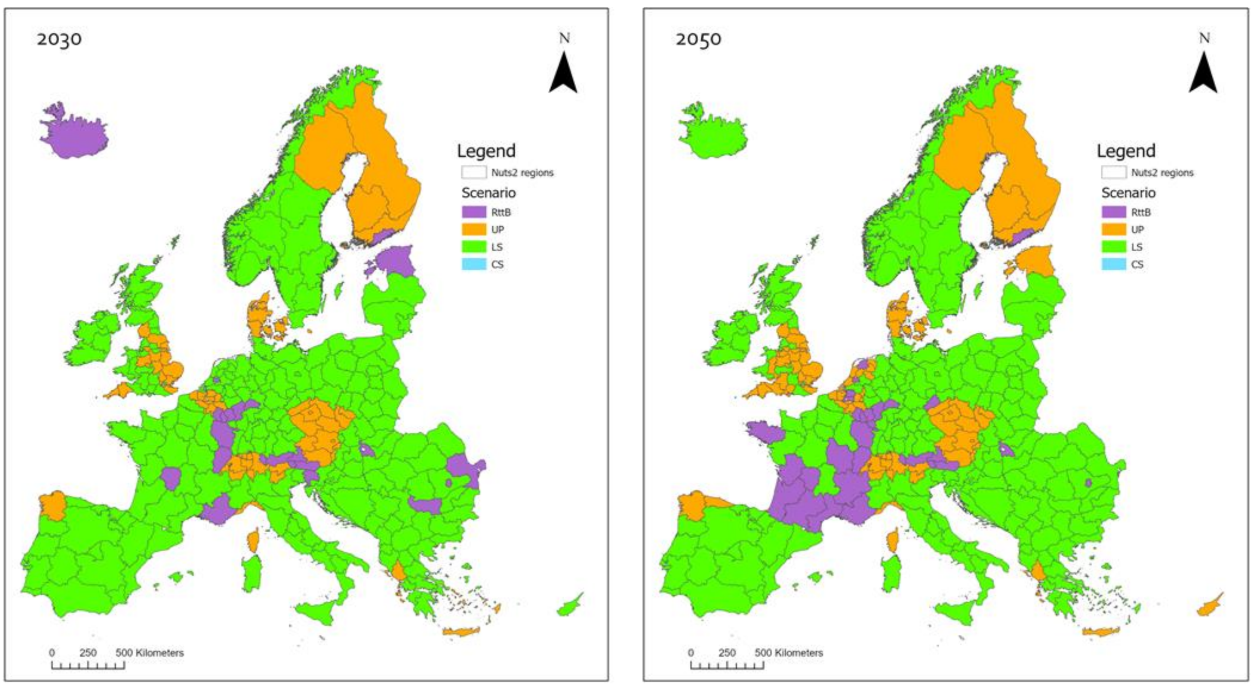

Figure 4.13: Scenarios leading to the highest gross margin in 2030 and 2050.

Soil organic carbon

Change in SOC compared to the situation in 2020 is clearly visible in Figures 4.14 - 4.17. In all scenarios, the change (in both directions) is larger for 2050 than for 2030. Comparing scenarios, the maps clearly show a more severe decrease in SOC for scenario Race to the Bottom than for the other scenarios. Scenario Caring and Sharing shows the most increase in SOC content, even though there are still areas where a decrease occurs. However, the arable areas in north-central Europe and north-central Spain that in the RttB scenario show a strong decrease in SOC, have turned into an increase in the Caring and Sharing scenario, as a result of the simulated SICS. The other two scenarios, Under Pressure and Local and Sustainable are in between in terms of SOC change. Local and Sustainable shows a slight increase in SOC, where Under Pressure still shows a slight decrease, but there is quite a bit of spatial variation and the patterns in these two scenarios are less clear.

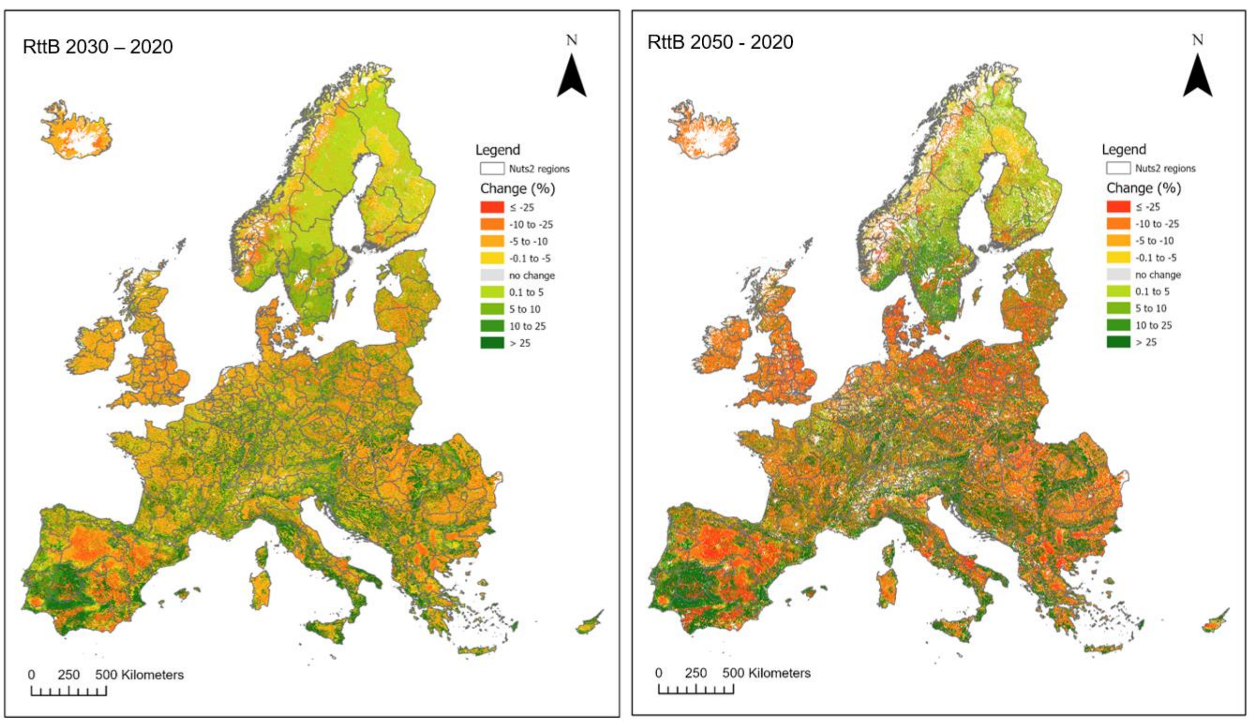

Figure 4.14: Change in SOC content (% of the content in 2020) for scenario Race to the Bottom in 2030 (left) and 2050 (right) compared to 2020.

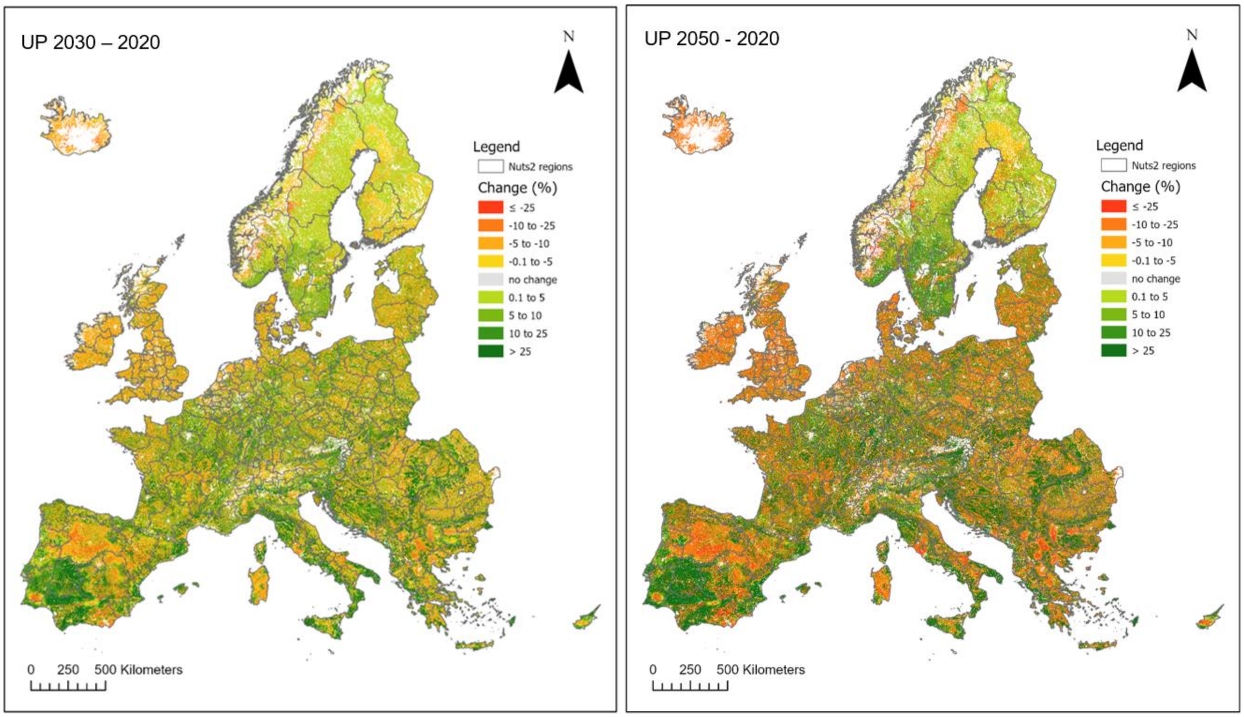

Figure 4.15: Change in SOC content (%) for scenario Under Pressure in 2030 (left) and 2050 (right) compared to 2020.

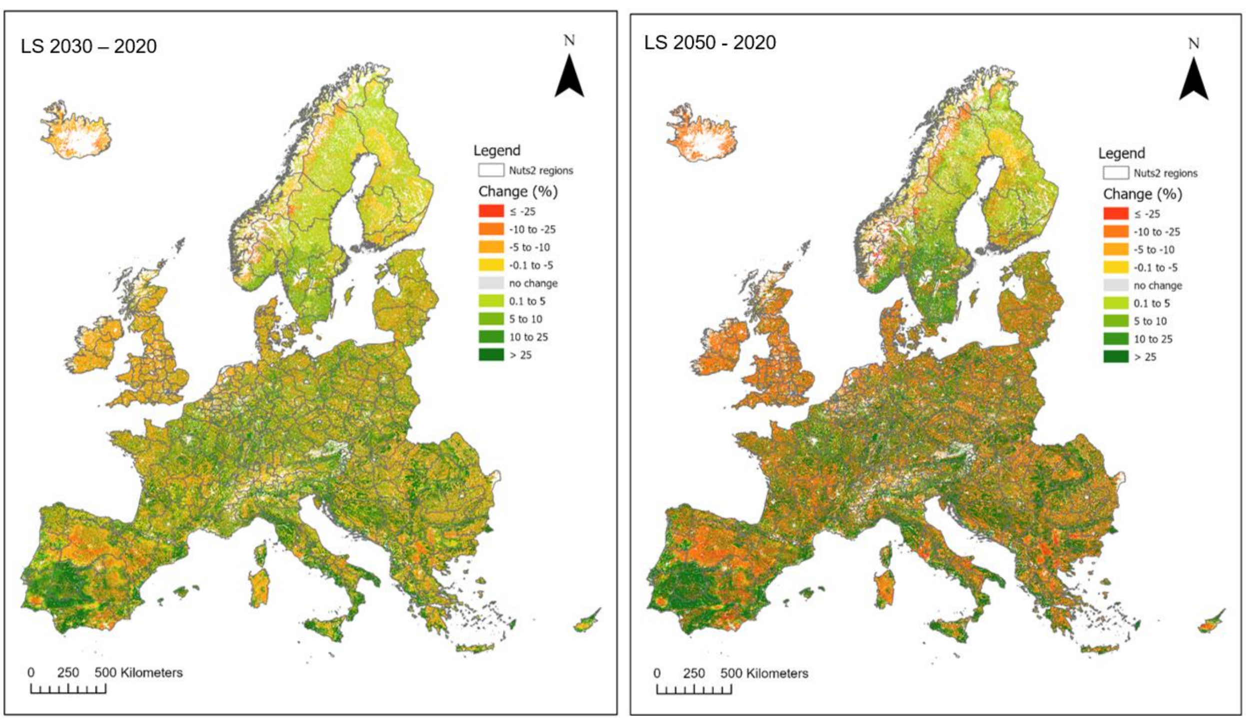

Figure 4.16: Change in SOC content (%) for scenario Local and Sustainable in 2030 (left) and 2050 (right) compared to 2020.

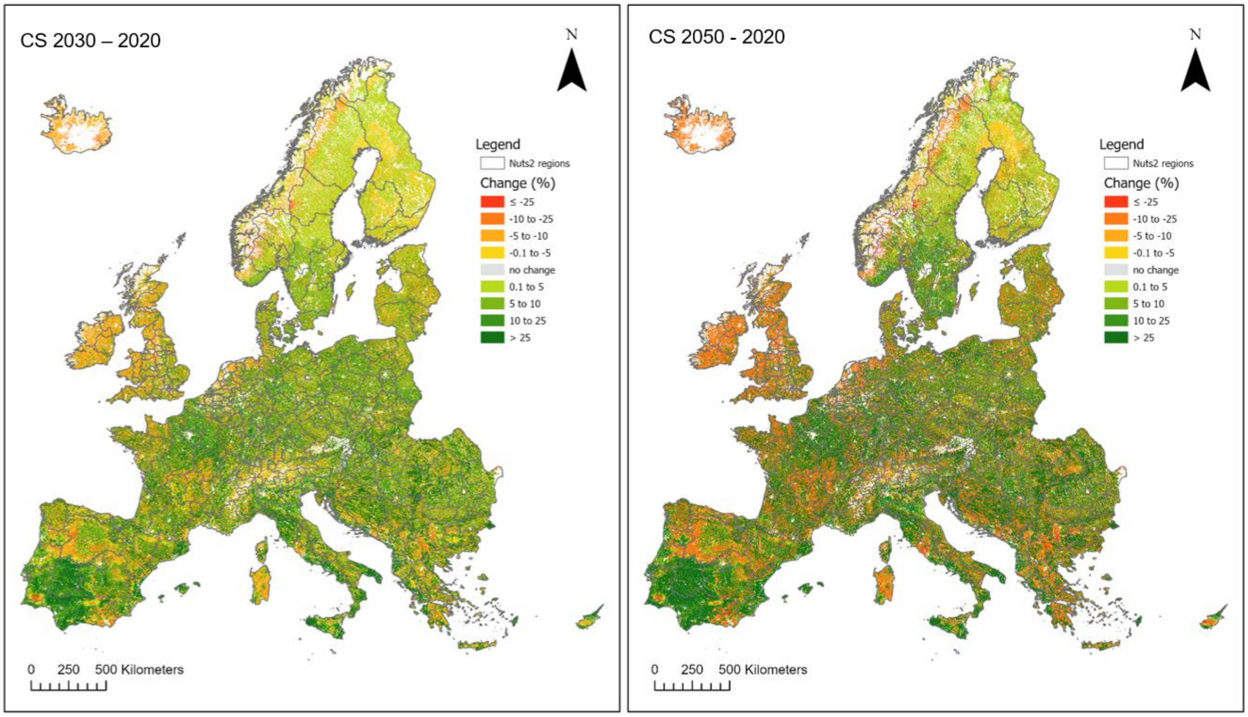

Figure 4.17: Change in SOC content (%) for scenario Caring and Sharing in 2030 (left) and 2050 (right) compared to 2020.

These changes in SOC are summarized in Figure 4.18 for climate regions and crops, comparing baseline conditions (2020) with the different scenarios for 2050. A first result is the large SOC increase in permanent crops for all scenarios, probably due to improved growth conditions throughout Europe; here the scenarios lead to few changes. SOC in annual crops show either stability (fodder maize, root crops) or some decrease (remaining crops), which is consistent for the different climate regions of Europe. Since biomass from annual crops is higher, here the warmer climate promotes faster SOC decomposition. Here, configurations for SICS in the scenarios LS and UP are able to counteract the predicted SOC decline, while scenario CS can even improve SOC content by 2050.

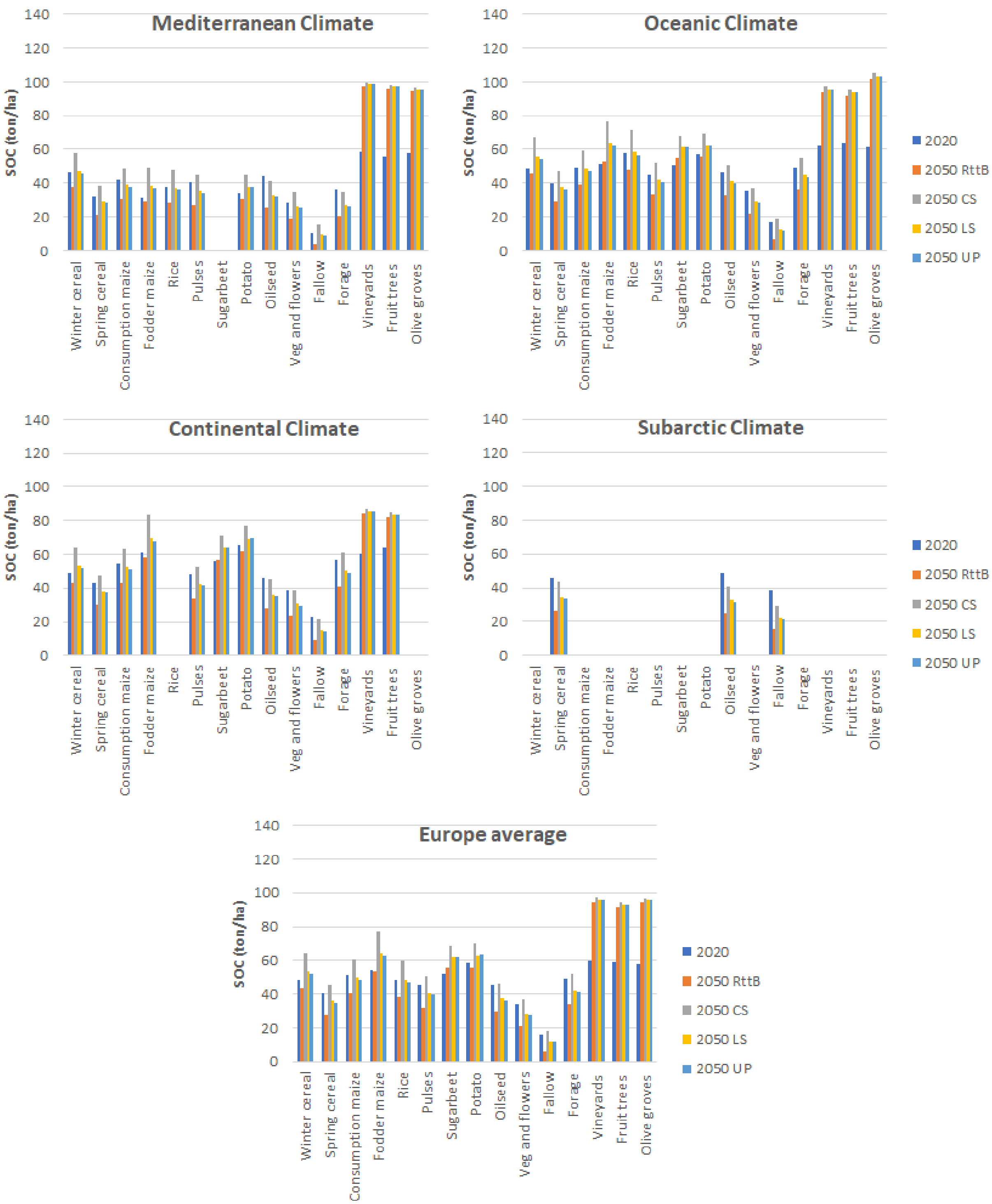

Figure 4.18: SOC content in 2050 for each scenario as a function of land use for arable crops, compared with baseline conditions for 2020.

Erosion

Figures 4.19 to 4.22 show the difference in simulated erosion for each scenario versus the situation in 2020, calculated for 2030 and 2050. Differences between scenarios and time horizons are less clear than for soil organic carbon, which is (partly) due to the variation in climate (mostly rainfall) that causes variation in erosion between years, independent of SICS. In the maps, the average over several years was taken (divided by the number of years), to reduce this variation.

In the Race to the Bottom scenario, both areas of increased erosion and decreased erosion compared to the situation in 2020 are visible. Similar to the SOC maps, when comparing between scenarios, the Caring & Sharing scenario shows the most widespread decrease in erosion, due to the effect of SICS. The remaining areas with increasing erosion are mainly steep mountain areas, where SICS are not applied. Especially areas in e.g., central Germany, eastern Europe and southern Spain showed increased erosion in the RttB scenario, while in the Caring & Sharing scenario they show decreased erosion. As in the SOC maps, the scenarios Under Pressure and Local & Sustainable are in between, but both maps also show wide-scale areas with decreased erosion as compared to 2020. Overall, the Race to the Bottom scenario is the only scenario where erosion across Europe increased (i.e., average of the entire 'erosion difference map'), while erosion decreased on average in the other scenarios, with highest decreased erosion in Caring & Sharing, followed by Under Pressure and Local & Sustainable.

Figure 4.23 summarizes changes to erosion versus the situation in 2020 per climate region and crop for all scenarios. In RttB, erosion tends to remain at similar levels as in baseline conditions (2020). Scenarios LS and UP are able to decrease erosion by one to two thirds, depending on the crop and region; their effectiveness is similar. In scenario CS, erosion is reduced by over 90% for all crops.

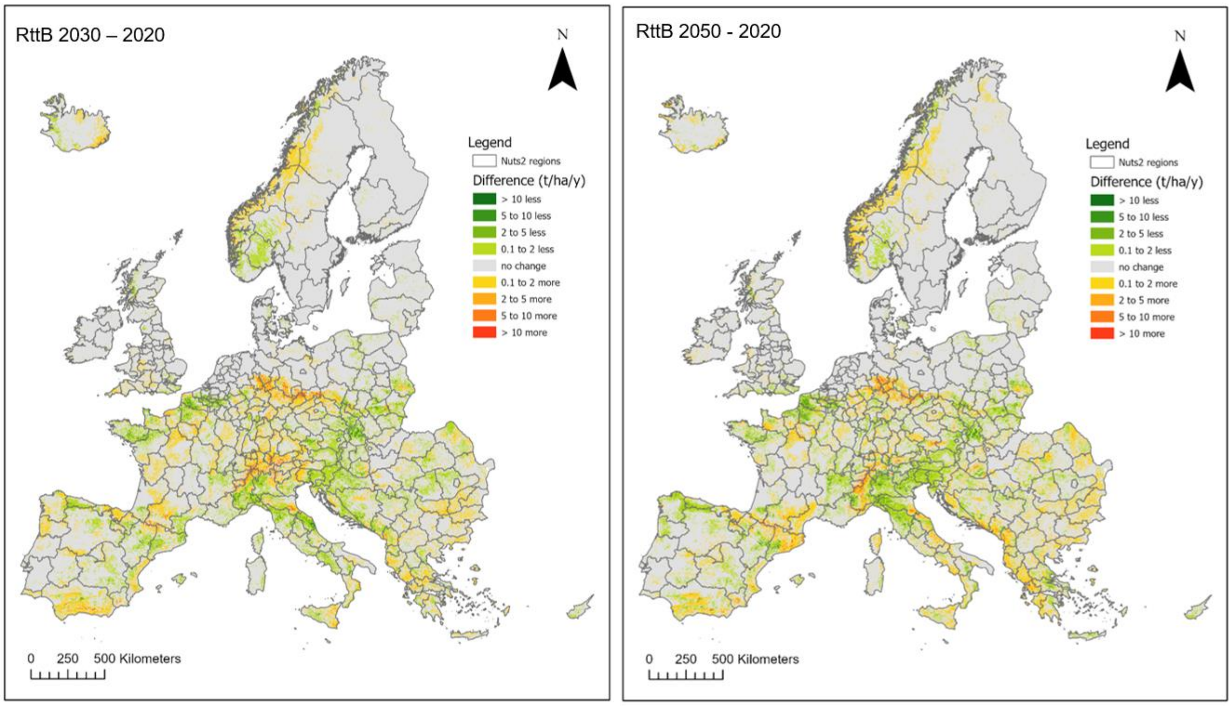

Figure 4.19: Difference in erosion (t/ha/y) for scenario Race to the Bottom for 2030 (left) and 2050 (right) as compared to 2020.

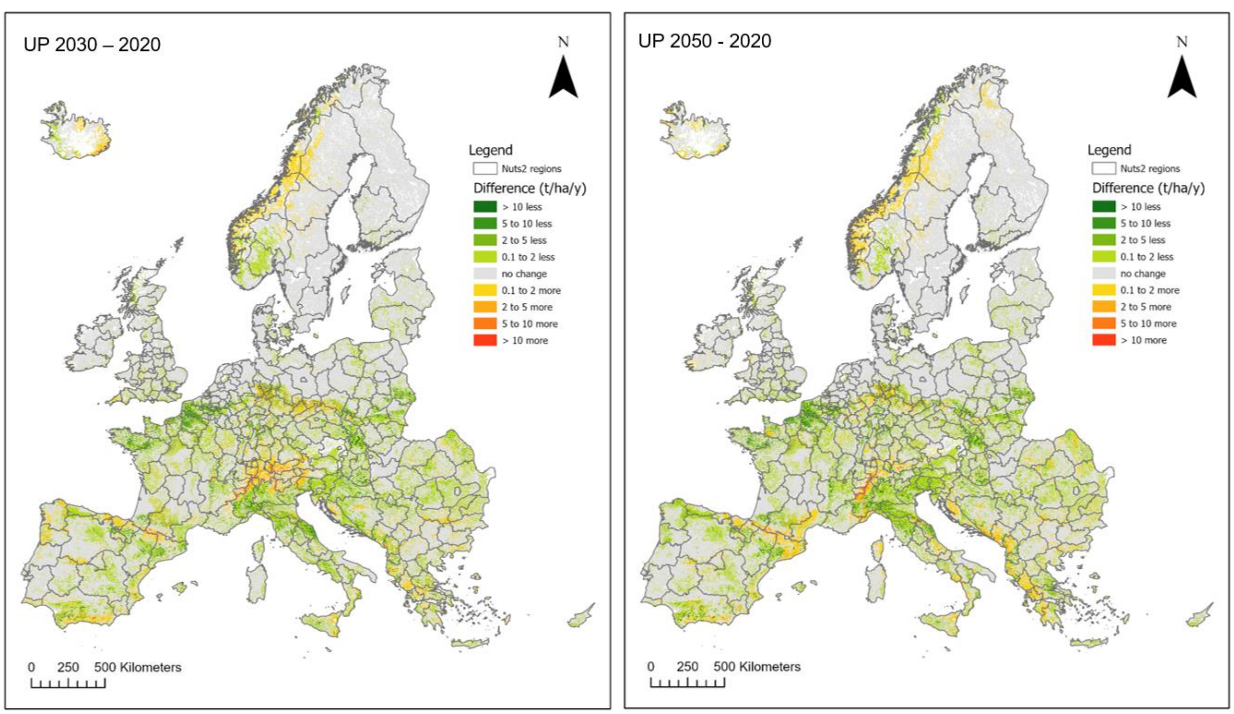

Figure 4.20: Difference in erosion (t/ha/y) for scenario Under Pressure for 2030 (left) and 2050 (right) as compared to 2020.

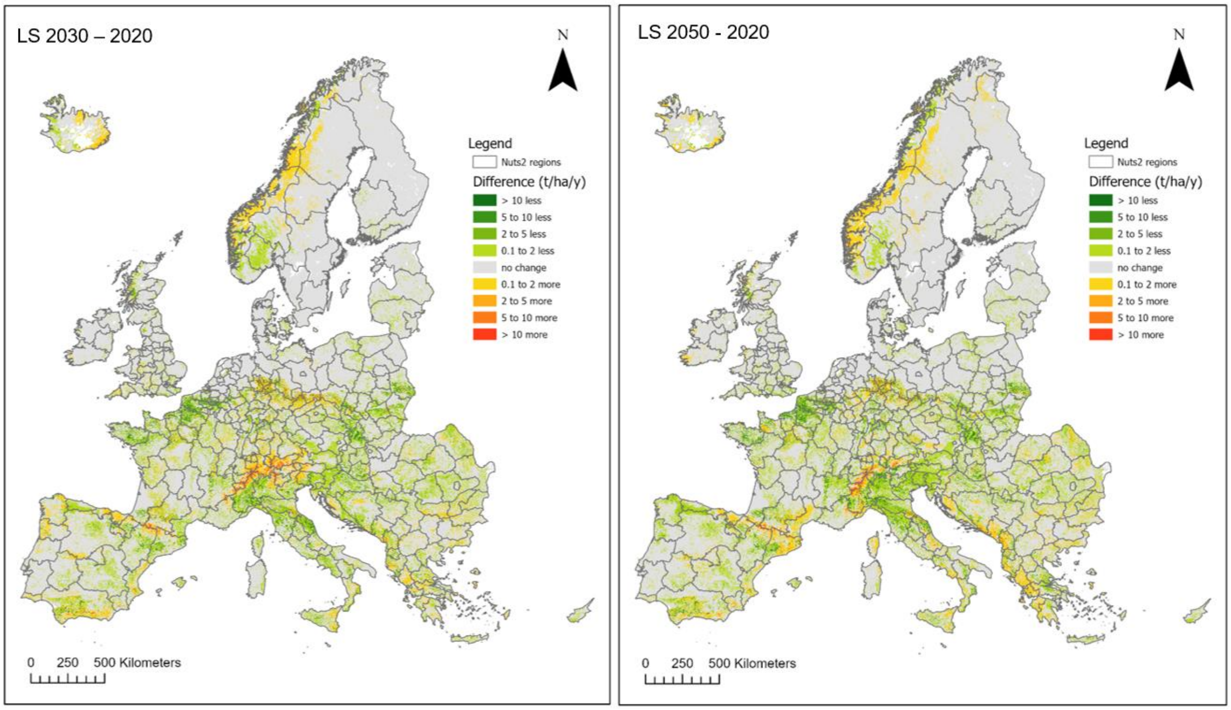

Figure 4.21: Difference in erosion (t/ha/y) for scenario Local & Sustainable for 2030 (left) and 2050 (right) as compared to 2020.

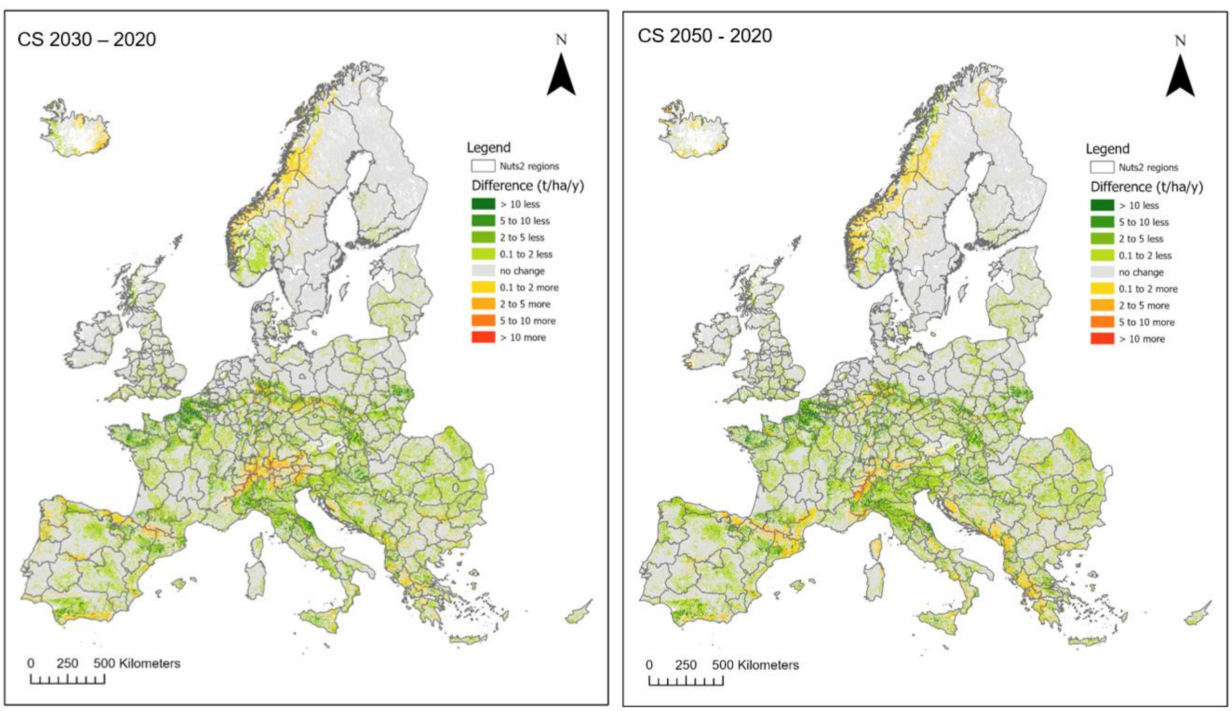

Figure 4.22: Difference in erosion (t/ha/y) for scenario Caring & Sharing for 2030 (left) and 2050 (right) as compared to 2020.

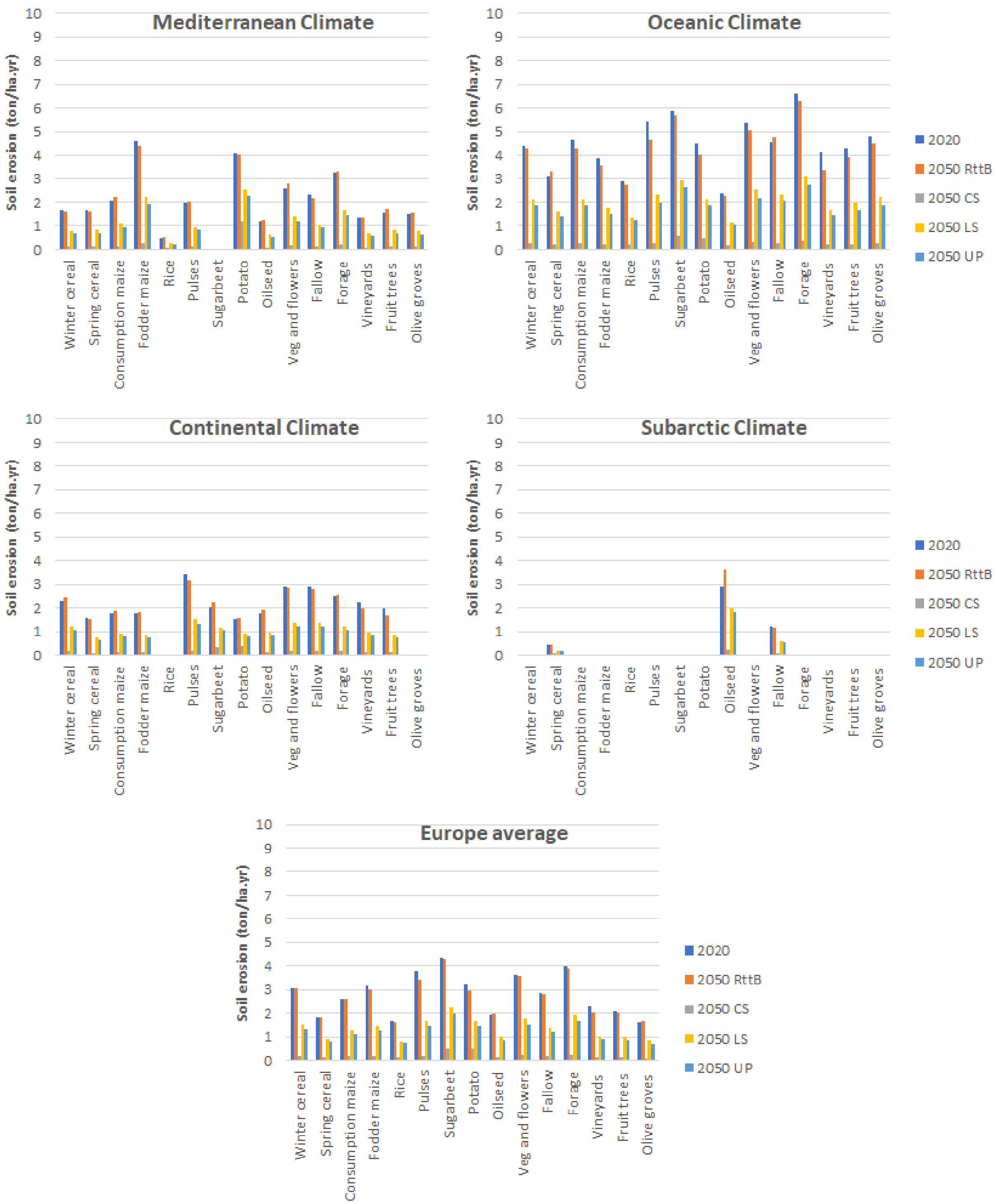

Figure 4.23: Soil erosion in 2050 for each scenario, compared with 2020

4.3.3. Reflection on model results

The model results presented in section 4.3.2 indicate that over time (until 2050), changes are expected in consumption, (domestic) production and net exports, yield (tonnes/ha), gross margin, soil organic carbon, and erosion. This is due to, amongst others, growth in population and GDP, changes in diets, trade flows, climate change, technological changes and changes in agricultural practices (i.e., through application of SICS). While some drivers are expected to result in impacts in the same direction in all scenarios and time windows (e.g., population growth is likely to lead to more consumption and SICS are expected to impact positively on sustainability indicators), other drivers could impact in very different ways. This is caused by regional differences, such as e.g., climate change impacting on yield levels, gross margins based on country specific crop prices and location specific biophysical conditions (e.g., soil nutrient, soil texture and climate conditions), or trade restrictions impacting on net exports of individual countries.

An important finding is that the Caring & Sharing scenario is likely to provide the best sustainability impacts (i.e., increased or stable SOC contents and reduced erosion rates) and the Race to the Bottom scenario the worst, with Local & Sustainable and Under Pressure scoring quite similar. Local & Sustainable seems to perform a bit better on soil organic carbon contents, while Under Pressure scores slightly better on erosion control.

Another important finding is that although the CS scenario leads to highest yield impacts, the gross margin of SICS uptake under this scenario is negative in many NUTS-2 regions. The most important factor contributing to this is the high implementation costs assumed when combinations of measures are implemented and the most extensive SICS (cover crops and mulching) are implemented on all agricultural land. Despite sustainability being high on the agenda in the CS scenario, (financial) policy support will therefore likely be needed to enhance uptake of SICS. Alternatively, value added through additional products and services, and valuation of environmental co-benefits could be a pathway to widespread SICS adoption. These aspects were beyond the scope of the modelling exercise.

Because of dietary changes, the Caring & Sharing scenario assumes the highest changes in the type of commodities consumed, as an increase in domestic use of cereals and pulses is assumed due to an increasing plant-based diet. However, with less meat consumption also comes a lower need for fodder, and this effect seems to be larger than increased land requirements to produce more cereals for human consumption. Due to the decreasing meat consumption also domestic use of maize seems to reduce in this scenario resulting from a lower demand for feed use. The RttB scenario has similar consumption patterns to those observed today. The other two scenarios are again taking a middle place, with the Under Pressure scenario being a bit closer to the CS scenario and the LS scenario a bit closer to the RttB scenario. It is interesting to note that impacts are not equal across Europe, as differences between the scenarios seem to be larger in EU-14 than in EU-N13.

Furthermore, with the Caring & Sharing scenario favouring local (within Europe) production compared to the other scenarios, and RttB assuming current trade flows, the area needed for production is higher in the Caring & Sharing scenario and therefore this scenario will have environmental impact due to a larger area dedicated to agricultural production, even though this production is more sustainable. On the other hand, this production may reduce degradation outside of Europe, and diminishes long distance hauling of products across the globe. The Local & Sustainable scenario also has a considerable part of the production within Europe (although less than the Caring and Sharing scenario), while the Under Pressure scenario has a production level in between Local & Sustainable and Race to the Bottom.

The cost-benefit analysis shows a mixed spatial pattern of scenarios that have the highest gross-margin across Europe. Reason for this is that the combination of drivers plays out differently in different parts of Europe, indicating the complexity of the issue and the importance of understanding local dynamics.

Model results are to a large extent based on input data, calibration, and scenario assumptions. These, by necessity, represent a simplification that can affect model results. For example, economic analysis focused on production of the main crop and did not consider other costs or benefits that may be obtained locally from application of SICS, such as protection against natural hazard or tourism activities. Furthermore, off-site effects of application of SICS could not be fully assessed. Most of these assumptions affect the 4 scenarios that have been investigated equally. As the aim of the modelling is to explore the interplay of the assumptions on the simulated processes, these limitations in the approach do not prevent a comparative analysis of the different scenarios. Nevertheless, it should be realised that model results do not represent a prediction of what would happen if a certain scenario would be implemented. Rather, the model results are meant as 'tools for thinking'.

4.4. Policy support

The scenarios, both in qualitative form through the storylines as well as in quantitative form through the modelled impacts, are meant to obtain insight in future uncertainties regarding sustainable and profitable agriculture in Europe, with the aim to design and stress-test policy actions for and across different scenarios and to provide policy recommendations that are 'future-proof'.

With the above aim in mind, participants of the second workshop (see Section 2.4) were asked to identify policy actions, or actions that can be supported by policy, that are expected to impact positively on the adoption of SICS and more sustainable practices in general (see also section 2.4). The main actions listed from the perspective of each scenario included:

From the perspective of scenario Race to the Bottom:

- Raise awareness for the need for SICS
- Include externalized costs into price through taxation based on current scientific knowledge
- Optimise technologies to minimise external inputs

From the perspective of scenario Local and Sustainable:

- Labelling and certifications, e.g., soil footprints displayed on products

- Need to reduce the costs of sustainably produced products so that they don't just become accessible for those who can afford them (or alternatively increase population purchasing power)
- Lighthouse projects - living examples of best (agricultural) practices

From the perspective of scenario Under Pressure:

- Integrated policies - ensure coherence, includes soil health as part of (future) sustainability assessment in impact assessments
- Improved communication, dissemination, and discussion on sustainable production methods. Advisory services can play an important role in this and also the directives can facilitate this process.
- Consumer taxation on products derived from 'unhealthy' soil practices to fund reinvestment into SICS

From the perspective of scenario Caring & Sharing:

- Fair subsidies are needed but controls on them are required to ensure that there is no abuse
- Create mechanisms to ensure feedback between legislators and stakeholders (permanent platforms/committees with representatives from the institutions and stakeholders)

Using these main actions per scenario, participants of the final EU-stakeholder workshop were asked to assess the actions across scenarios to understand which actions are relevant to tackle certain developments within a specific scenario and which actions are robust across a range of scenarios (see also Section 2.4)

Most actions were found likely to succeed under the Caring & Sharing scenario. This is in line with expectation, as this scenario is designed to have low challenges to either mandatory or voluntary instruments. An action that wasn't expected to be very useful was *Consumer taxation on products derived from 'unhealthy' soil practices to fund reinvestment into SICS*, as there was the assumption that taxation wouldn't be the best mechanism in a scenario with a wide-shared understanding on the importance of sustainable practices to maintain natural resources. Also the *Need to reduce the costs of sustainably produced products* and *Fair subsidies ensured but controls on them to ensure that there is no abuse*, were not seen as actions most likely to be successful in this scenario, due to the expected mindset of the population.

On the contrary, the policy actions that did not score well for the Caring and Sharing scenario did seem to be favourable for the Race to the Bottom scenario: *Need to reduce the costs of sustainably produced products*, *Fair subsidies ensured but controls on them to ensure that there is no abuse*, and *Consumer taxation on products derived from 'unhealthy' soil practices to fund reinvestment into SICS*.

In the Under Pressure scenario policy actions that rank best are those with a strong policy or technology element: *Integrated policies*, *Consumer taxation on products derived from 'unhealthy' soil practices to fund reinvestment into SICS*, *Include externalized costs into price (tax) based on current scientific knowledge*, and *Optimise technologies to minimise external inputs*.

Finally, actions that are expected to be successful under the Local & Sustainable scenario are those that enhance the understanding of and stimulate good agricultural practices: *Labelling and certifications*, *Lighthouse projects*, *Raise awareness for the need for SICS*, as well as *Integrated policies* and *Optimise technologies to minimise external inputs*.

It is interesting to note that most actions score well under two and sometimes three scenarios, however none of the actions scores really well on all four scenarios. An important conclusion that can be drawn from this is that understanding the socio-economic conditions well is critical in the design of policies, and policies need to be tailored to target the specific needs expected under different (socio-economic) conditions.

Combining these findings with the scenario quantification (Section 4.3), we conclude that considering different drivers, their interplay and the acknowledgement that differences occur spatially, are all critical in designing 'fit-for-purpose' policy actions. As section 4.3 showed, the different scenarios are expected to have different effects on e.g., yield, farm economy, SOC and erosion. Which of these factors has locally the highest priority will also differ across Europe, and may even be different for different stakeholders within a region. Such priorities determine what the main purpose of policy actions would be. Hence, in addition to variation in drivers, their interplay, and spatial differences, there will also be differences in purpose of the policy actions as they are implemented in different parts of Europe. The scenarios that have been developed can, for different priorities, provide insight on what might be needed to achieve policy aims. In this context, the narrative scenarios and their model implementation each provide their own insights, where the qualitative aspects from the narratives and the quantitative and spatially explicit outcomes of the modelling supplement each other.

The participatory scenario development enriches the future pathways, as expressed by the scenarios, while the modelling facilitates systems thinking and enhances the understanding of the causal relationships between domestic, consumption, production, land use, yield, profitability, SOC and erosion, in space and over time. In the assessment of actions, the modelling is able to calculate the expected impact of policy options under various conditions, while the participatory activities allow to incorporate those assessment criteria that cannot be modelled, especially related to the socio-cultural and political aspects.

5. Conclusions and recommendations

In order to deal with changing conditions for agriculture in Europe, a storyline, simulation and policy support approach was developed (Section 2). This approach comprises a participatory development of narrative scenarios, a quantification of these scenarios using an integrated assessment model, and participatory policy support activities using the developed scenarios to assess the feasibility of proposed options.

The developed storylines (4.2) describe different pathways for European agriculture depending on the degree to which voluntary and mandatory policy instruments to encourage sustainable agriculture can be implemented. Together, they aim to provide a rich picture of how the future might unfold, taking into account main socio-cultural, technological, economic, environmental, and political (STEEP) drivers of change and their related uncertainties. Better understanding the potential directions into which our future may unfold, helps to make better decisions on the actions we take at present. They can also help us to design specific actions to counter unwanted development or stress-test actions we plan to implement.

The storylines were complemented with quantitative modelling using the SoilCare Integrated Assessment Model (IAM), developed as part of the project. The SoilCare IAM has the aim to assess the impact of cropping systems and agronomic measures throughout Europe at a high level of spatial detail (100-500 m.). The SoilCare IAM was used to provide input maps for the applicability and relevance of SICS (D6.1), and to perform impact assessment of the developed pathways on domestic consumption, net exports, crop production (including yield and gross margin), land use, soil organic carbon and erosion, in current (2020) and future (2030, 2050) conditions. The results of the SoilCare IAM were used to quantify narrative scenarios of pathways for European agriculture until 2050.

The SoilCare scenarios were constructed and used to provide policy support through a series of activities. These activities included interviews, workshops, and webinars with stakeholders at the European level, and are outlined in detail in sections 2 and 4.1., all leading up to a final workshop, focused on policy actions. Here, policy actions were identified for individual scenarios, but also assessed across all four scenarios. We found that most actions score well under two and sometimes three scenarios, e.g., labelling and certifications and lighthouse projects are expected to be successful under the scenarios Local & Sustainable and Caring & Sharing, while consumer taxation is likely to be successful in Under Pressure and Race to the Bottom. However, none of the actions score really well on all four scenarios. An important conclusion that can be drawn from this is that understanding the socio-economic conditions well is critical in the design of policies, and policies need to be selected and tailored to target the specific needs expected under different (STEEP) conditions.

Combining these findings with the scenario quantification (Section 4.3), we conclude that considering different drivers, their interplay and the acknowledgement that differences occur spatially, are all critical in designing 'fit-for-purpose' policy actions. As section 4.3 showed, the different scenarios are expected to have different effects on e.g., yield, farm economy, SOC and erosion. Which of these factors has locally the highest priority will also differ across Europe, and may even be different for different stakeholders within a region. Such priorities determine what the main purpose of policy actions would be. Hence, in addition to variation in drivers, their interplay, and spatial differences, there will also be differences in purpose of the policy actions as they are implemented in different parts of Europe. The scenarios that have been developed can, for different priorities, provide insight on what might be needed to achieve policy aims. In this context, the narrative scenarios and their model implementation each provide their own insights, where the qualitative aspects from the narratives and the quantitative and spatially explicit outcomes of the modelling supplement each other.

The participatory scenario development enriches the future pathways, while the modelling facilitates systems thinking and enhances the understanding of the causal relationships in space and over time. In the assessment of actions, the modelling is able to calculate the expected impact of policy options under various conditions, while the participatory activities allow to incorporate those assessment criteria that cannot be modelled, especially related to the socio-cultural and political aspects.

Although the online participatory approach (that was necessary due to COVID-19) was challenging and has its limitations due to limited possibility for (in)formal personal interactions, organising an online webinar and workshop has allowed us to reach a much wider group of stakeholders from countries all over Europe who would not have been able to join an in-person meeting. For future work we would therefore recommend a combination of in-person and online participatory activities.

The narratives of the scenarios, their translation into outcomes for agricultural production and environmental effects, and the proposed actions in response to these by stakeholders could be used in various ways beyond the SoilCare project:

- The narratives could be used to inform citizens and policy makers on how agriculture in Europe could look like in 2050, and to inform strategies for development of agro-food companies;
- The narratives and proposed policy actions could be used to devise strategies for the operationalization of the Farm-to-Fork Strategy of the EU;
- Model outcomes from the four scenarios could be used to simulate impacts of eco-schemes designed by Member States under the new CAP or to guide the design of new eco-schemes (e.g. by using results showing which SICS would be effective where);
- Model outcomes could be integrated in the Interactive CAP Indicator Dashboards of the European Commission;
- The complex systems modelling approach of the IAM, and its embedding in a participatory scenario development process, provides an innovative high-level science and innovation approach that allows putting soil and land management issues and actions in a broader context, offering researchers and innovation managers new tools to explore the impacts of potential (system) innovations.

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Annex 1: Metronamica

A1.1. Overview of model information

Name of the model

Metronamica

Scope and aim of the model

Exploration of land use dynamics under the influence of economic and demographic changes, and impact assessment of spatially-explicit zoning and infrastructure policies

Main concepts and modelling paradigm

Metronamica is a cellular automata (CA) based model that simulates land use changes over time based on a competition for space principle. Actors, represented by their land use classes, determine the most preferential locations for their activity and will try to occupy these locations as long as there is sufficient demand for their activity. Whether they will be able to occupy their most preferential locations depends on their relative political and economic strength (compared to that of the other actors), and the support or restrictions posed by planning and policy. Regional demands, as well as locational characteristics such as physical suitability for land uses, zoning regulations, accessibility, the type or land use occupying the location and the neighbouring land uses all play a role in determining future land use changes.

Scale the model has been applied to and can be applied to

The model has so far been applied to cities, regions, countries and continents and could also be applied to the global scale. Although the model has been set up for small areas, we normally advice to apply it to cities or regions with more than 100 inhabitants as we feel that beyond this size exploratory scenario simulations become more relevant.

Is the model spatially explicit?

Yes. The model operates on a grid, with network overlays.

Spatial resolution of the model and flexibility of this resolution

The model has so far been applied to grid cells with a resolution varying between 25 m. and 1000 m. To simulate local dynamics well, we advise against using a very coarse resolution, although this also depends on the data availability, the local context (e.g. homogeneity of the area), the focus of the study and the requirements put on the computation time. We also advice against using a resolution more detailed than 25 m. as this goes against the concept of the model in most cases.

Does the model include temporal dynamics?

Yes. Temporal dynamics are crucial in the model as results for a time t+1 build on results from time t.

Temporal resolution of the model and flexibility of this resolution

The model works on an annual resolution.

External drivers included

Metronamica uses land use demands as an input. In the single layer (SL) version of the model these demands are entered as area totals per land use class. In the multiple layer (ML) version of the model, the user can enter a time series of population and employment (or GDP) figures which are next converted into land use demands for the socio-economic land use classes. For classes that require an external demand but are not related to any particular socio-economic activity (e.g. non-production forests and other nature) users can still enter an area demand.

Furthermore, it is possible to enter derived information from climate scenarios (e.g. rainfall, temperature, occurrence of flood or fire hazard) as maps included in the physical suitability driver for land uses allocation in different years.

Management options included

Main management options are the inclusion of spatial plan indicated where activities (land uses) are allowed, restricted (in various degrees) or actively stimulated as well as the construction and adaptation of infrastructure networks.

Indicators calculated

Metronamica includes a set of indicator algorithms that allow for an easy development of specific indicators (maps and aggregate statistics, both updated at each simulation step). Included algorithms with examples are:

- 'Distance to', e.g. indicator showing the distance to work locations from residential locations.
- 'Cluster', e.g. indicator of urban clusters of various sizes.
- 'Mapping', e.g. soil sealing indicator by mapping all urban land use classes.
- 'Mask', e.g. flood risk indicator by applying a flood occurrence map and combining this with the consequence (land use) within the area prone to flooding to calculate the flood risk
- 'Neighbourhood', e.g. a quality of life indicator based on the neighbouring land uses of residential cells.
- 'Land use change', e.g. land abandonment, deforestation and/or reforestation.

Input data required and desired

- Land use map.
- Base maps for suitability, such as soil type, elevation, rainfall, temperature, probability of flood occurrence, soil moisture, groundwater tables), when relevant for different years.
- Base maps for zoning, such as forest reserves, Ramsar sites, urban expansion plans.
- Base maps for accessibility, such as road network, train network or stations, irrigation network.
- Population and job/gdp data.

All maps can be provided as shape files. For the network maps this is a requirement. The other maps will be converted into raster files.

A land use map and a road network are required. All additional data is desired to make the application more realistic. There is no need to fill the model with all possible data available. A selection needs to be made regarding the main drivers for land use change and land use allocation.

Parameters required and desired

- Interaction rules between land use classes representing the human behaviour, including attraction and repulsion of neighbouring land uses, inertia, ease of conversion, strength to occupy locations of interest.
- Parameters to interpret the suitability base maps in terms of suitability for each land use (of a scale of 0-1 with 0 being unsuitable and 1 being perfectly suitable.
- Quantitative interpretation of qualitative zoning statuses (e.g. weakly restricted or actively stimulated).
- Accessibility parameters regarding the importance and distance decay of the various infrastructure network elements for the land uses included.

Data required for calibration and validation

- Land use maps for previous years (Ideally for 2 historic years previous to the map for the current situation as listed under the input data. Depending on the amount of change that has occurred in the past period.
- Main changes in infrastructure networks, zoning and suitability if they have taken place.
- Narrative information on historic land use change causes and processes.

Calibration and validation process

When setting up a new application, the following steps are generally applied for finding an appropriate parameter set and assessing its quality. The steps below describe those carried out as part of a desk study. Where possible it is advised to complement the steps with expert and or stakeholder input.

1. As part of the data analysis the current situation and historic developments are analysed. This includes analysing the temporal change in total area surface for various land uses as well as the change in landscape structure. Regarding the latter, metrics such as the clumpiness index and the rank size distribution are used in conjunction with a visual inspection of the developments. Furthermore, the enrichment factor is used to analyse the over- and underrepresentation of certain land uses in the neighbourhood of changed land uses.

2. Model set-up includes a set of choices relevant for setting up the model to a specific region and context. In CA-based land use modelling main choices are related to the decision on the area extent, the applied resolution and the selection of land use classes to be modelled, where finding a balance between providing additional information and creating a false sense of accuracy is often a crucial point of discussion.

3. During the calibration, parameter values are set and fine-tuned and subsequently the model is assessed on its behaviour and results, frequently over a historic calibration period. Difficulties in calibrating CA-based land use models mainly relate to the large number of parameters that need to be set, the limited availability of time series of land use maps, and finding objective ways to assess the quality of the calibration. Regarding the latter, progress has been made over the past years, which has resulted in the use of neutral models to act as a benchmark for quality assessment, together with the use of objective measures to complement the more subjective visual assessment. To assess the quality of the calibration we take into account the predictive accuracy, which is the ability of the model to accurately simulate actual land use patterns; and the process accuracy, the extent to which the modelled processes are consistent with real world processes. Main indicators used for assessing the quality of the calibration are indicators for location agreement, such as Fuzzy Kappa and Fuzzy Kappa Simulation; indicators for

landscape structure agreement, such as the clumpiness index, the fractal dimension, the rank size distribution, and the enrichment factor; and visual inspection.

4. During the validation, the model's behaviour and results, based on the parameters settings obtained during the calibration, are assessed over a data set independent from the one used as part of the calibration. This usually results in an evaluation of the model's behaviour over a different historic period; although other independent data sets are equally valid. Assessment criteria are the same as for the calibration.
5. Finally, the model is tested and evaluated on its long-term behaviour, which includes a long-term simulation with the calibration parameters, a number of tests with extreme scenarios to assess the robustness of the model, a number of tests to assess the sensitivity of model results on small changes to the parameter settings and some tests to assess the impact of the main perceived uncertainties.

Outputs

- Land use maps (raster files).
- Indicator maps derived from the land use maps (raster files).

Run-time of the model

Most applications run in the order of minutes for a 30-50 year period, but given the large area extent and high resolution, an application for Europe at 100 m resolution is likely to run much slower.

Availability of model

Yes, Metronamica is available without additional costs as part of the project.

Availability of model developer

Yes, Metronamica is developed and being maintained at RIKS.

Availability of source code

Yes, to the consortium partners.

Programming language

C++

Possibility to re-use worldwide

Yes.

Ability to adapt to meet requirements

High.

Common uses in combination with other models

- Integration with socio-economic models (age-cohort, CGE, statistical economic models, input-output models), e.g. Xplorah, ISE, WISE, LUMOCAP
- Integration with transport models, e.g. Metronamica LUT, Xplorah
- Integration with hazard models (coastal inundation, river flood, bushfire, earthquake), e.g. UNHaRMED
- Integration with bio-physical models (hydrology, water quality, erosion, salinization, vegetation dynamics), e.g. MedAction, DeSurvey
- Integration with agent-based approaches, e.g. MedAction

Potential and limitation for integration with other models

- Integration works especially well with other dynamic simulation models. Dynamic coupling with equilibrium approaches is harder.

Additional remarks

None.

A1.2. Input data description and sources

Main inputs include an initial land use map, infrastructure layers (at least a road map, although train, bus, and irrigation networks are relevant too), zoning base layers (such as protected natural areas and urban expansion plans) and base layers for suitability.

To align all modelling activities and best support the aims of the project, a dedicated land use was developed based on Corine Land Cover 2018 (CLC 2018) (see Figure A1.1) (https://land.copernicus.eu/pan-european/corine-land-cover) and a range of crop types from Eurostat (https://ec.europa.eu/eurostat). The crop types, for which area information was available at NUTS-2 level, were included in the agricultural areas of the CLC 2018 map. In case the agricultural areas were not large enough to meet the area provided by Eurostat, natural grasslands and scrub areas were also used. In case the agricultural areas provided by Eurostat were smaller than the agricultural areas on the CLC 2018 map, remaining areas were labelled as natural grasslands and scrub. This resulted in the SoilCare IAM map shown in Figure A1.2.

For the urban functions the base layers consist of the slope and the human activity layer, for the agricultural and natural uses the suitability layers calculated by the land suitability model component are used. These are processed results from the biophysical models and hence based on N, P, K, SOM, soil types and slope. As zoning base map the NATURA2000 data was used (https://ec.europa.eu/environment/nature/natura2000/index_en.htm). For transport data use is made from OpenStreetMap (https://www.openstreetmap.org).

For calibration use has been made of data from Eurostat and a series of Corine Land Cover maps (1990, 2000, 2006, 2012, 2018).

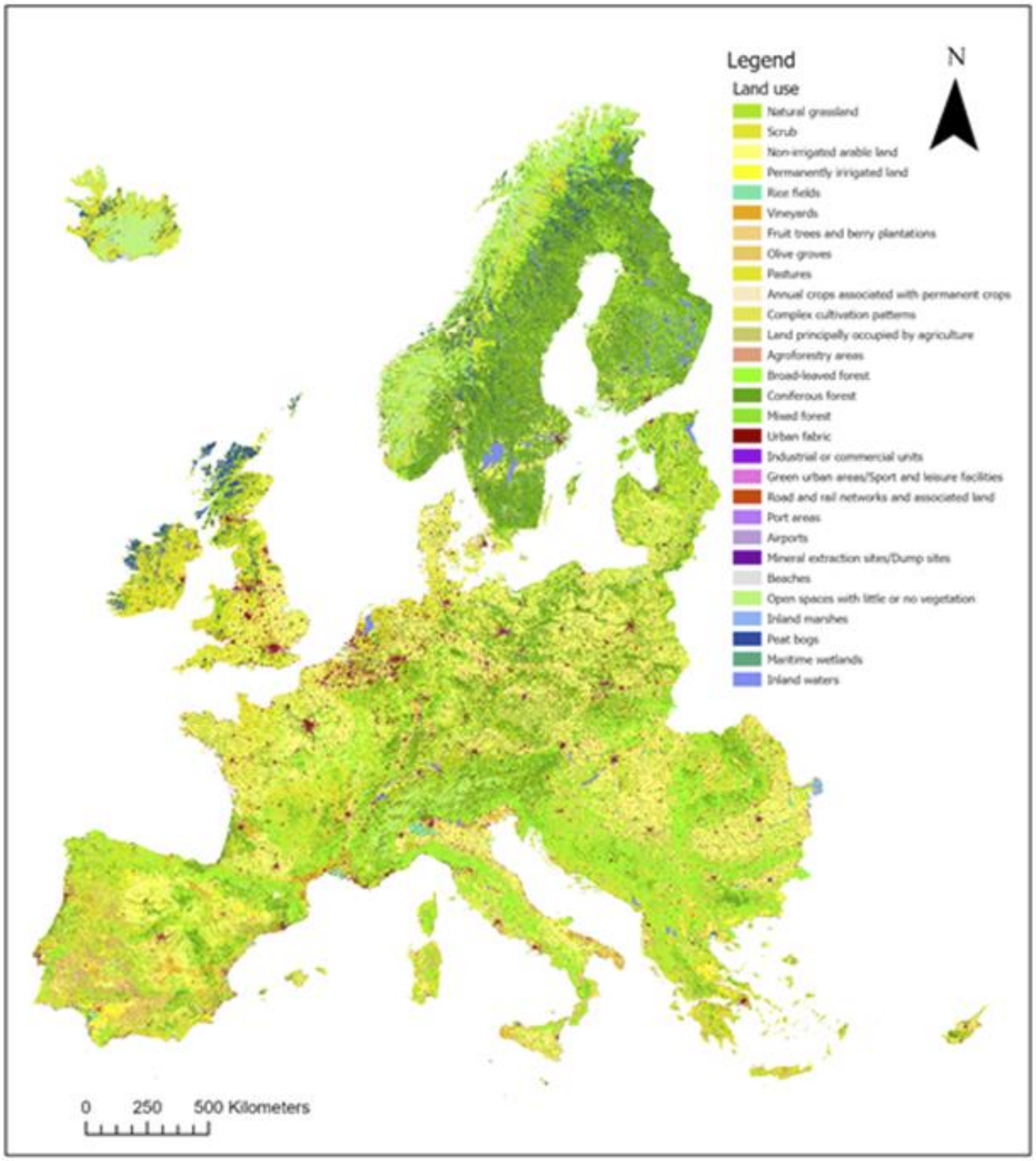

Figure A1.1: Corine Land Cover 2018 map.

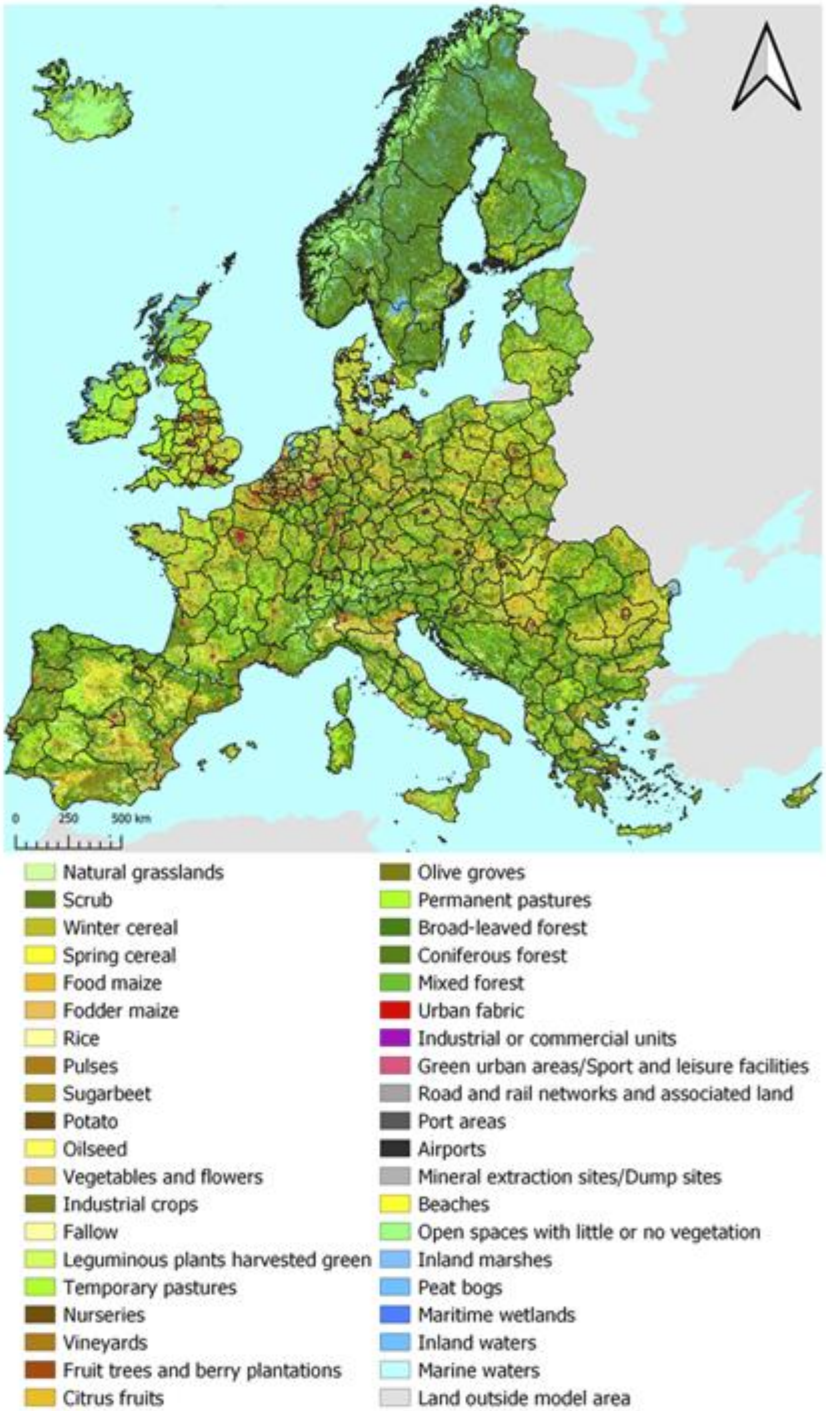

Figure A1.2: SoilCare IAM initial (2018) land use map.

A1.3. Parameterization, tuning and performance assessment

A1.3.1. Application and calibration process

When setting up a new application, the following steps are generally applied for finding an appropriate parameter set and assessing its quality. The steps below describe those carried out as part of a desk study. Where possible it is advised to complement the steps with expert and or stakeholder input.

1. As part of the data analysis the current situation and historic developments are analysed. This includes analysing the temporal change in total area surface for various land uses as well as the change in landscape structure. Regarding the latter, metrics such as the clumpiness index and the rank size distribution are used in conjunction with a visual inspection of the developments. Furthermore, the enrichment factor is used to analyse the over- and underrepresentation of certain land uses in the neighbourhood of changed land uses.

2. Model set-up includes a set of choices relevant for setting up the model to a specific region and context. In CA-based land use modelling main choices are related to the decision on the area extent, the applied resolution and the selection of land use classes to be modelled, where finding a balance between providing additional information and creating a false sense of accuracy is often a crucial point of discussion.

3. During the calibration, parameter values are set and fine-tuned and subsequently the model is assessed on its behaviour and results, frequently over a historic calibration period. Difficulties in calibrating CA-based land use models mainly relate to the large number of parameters that need to be set, the limited availability of time series of land use maps, and finding objective ways to assess the quality of the calibration. Regarding the latter, progress has been made over the past years, which has resulted in the use of neutral models to act as a benchmark for quality assessment, together with the use of objective measures to complement the more subjective visual assessment. To assess the quality of the calibration we take into account the predictive accuracy, which is the ability

of the model to accurately simulate actual land use patterns; and the process accuracy, the extent to which the modelled processes are consistent with real world processes. Main indicators used for assessing the quality of the calibration are indicators for location agreement, such as Fuzzy Kappa and Fuzzy Kappa Simulation; indicators for landscape structure agreement, such as the clumpiness index, the fractal dimension, the rank size distribution, and the enrichment factor; and visual inspection.

4. During the validation, the model's behaviour and results, based on the parameters settings obtained during the calibration, are assessed over a data set independent from the one used as part of the calibration. This usually results in an evaluation of the model's behaviour over a different historic period; although other independent data sets are equally valid. Assessment criteria are the same as for the calibration.

5. Finally, the model is tested and evaluated on its long-term behaviour, which includes a long-term simulation with the calibration parameters, a number of tests with extreme scenarios to assess the robustness of the model, a number of tests to assess the sensitivity of model results on small changes to the parameter settings and some tests to assess the impact of the main perceived uncertainties.

A1.3.2. Conceptual decisions and calibration results

Main conceptual decisions were made for the SoilCare IAM as an integrated model:

The SoilCare IAM includes 37 countries: the European Union countries, Albania, Bosnia-Herzegovina, Iceland, Kosovo, North Macedonia, Norway, Montenegro, Serbia, Switzerlandand, UK and operates at a spatial resolution of 100-500 m. grid cells. For the SoilCare project the temporal horizon is set to 2050. Models operate at a temporal resolution of months and years in line with the processes they represent.

The SoilCare IAM includes a range of agricultural and non-agricultural land uses and crop types, which have been selected to meet project objectives while taking into account the modelling capabilities and limitations:

- Arable crops and land uses: winter cereal, spring cereal, grain maize, fodder maize, rice, pulses, sugarbeet, potato, oilseed, vegetables & flowers, industrial crops, fallow.
- Permanent crops and land uses: Nurseries, vineyards, fruit trees and berry plantations, citrus fruits.
- Grass and grazing lands: natural grasslands, temporary grasslands, leguminous plants harvested green.
- Forest land uses: broad-leaved forest, coniferous forest, mixed forest.
- Urban land uses: urban fabric, industrial or commercial units, green urban areas and leisure, road and rail infrastructure, port areas, airports, mining and dump sites,
- Natural uses: beaches, open spaces with little or no vegetation, inland marshes, peat bogs, maritime wetlands, inland waters and marine waters.

Not all crop types and uses can or need to be used by all models. An overview of how the different land uses and crop types link throughout the different models is provided in Table A1.1.

Table A1.1: Overview of crop types as used by the different models in the SoilCare IAM

SoilCare crop classification	AGMEMOD	PESERA	QUEFTS	MITERRA
Winter cereal	Sum of Cereals	Arable: winter cereal	Wheat	Sum of Cereals
Spring cereal	Sum of Cereals	Arable: spring cereal	Wheat	Sum of Cereals
Grain maize	Cereals: Corn	Arable: grain maize	Maize	Grain maize
Fodder Maize	Cereals: Corn	Arable: fodder maize	Maize	Fodder maize
Rice	Rice	Arable: Lowland rice	Rice	Paddy rice
Pulses	Pulses Soya	Arable: Pulses	Pulses / Soybean	Pulses Soya
Sugarbeet	Sugarbeet	Arable: Sugarbeet	Sugarbeet	Sugarbeet Fodder root crops
Potato	Potato	Arable: Potato	Potato	Potatoes
Oilseed	Sum of Oilseeds	Arable: Oilseed	Rapeseed	Rape Sunflower Other oils
Veg and flowers	-	Arable: Veg and flower	-	Tomatoes Other vegetables Flowers Other crops
Industrial crops	-	Arable: Veg and flower	-	Flax and hemp Tobacco Other industrial crops
Nurseries	-	Fruit trees	-	Nurseries
Fallow	-	Arable: Fallow	-	Fallow land, Set aside idling
Vineyards	-	Vineyards	-	Table grapes, Wine
Fruit trees and berry plantations	-	Fruit trees	-	Apples, pears and peaches; Citrus fruits; Other fruits;
Olive groves	-	Olive groves	-	Olives for oil, Table olives
Pastures	Sum of 3 livestock categories Livestock: cattle Livestock: pigs Livestock: goats and sheep	Pastures/grassland	-	Gras and grazings

Annex 2: PESERA

A2.1. Overview of model information

Name of the model

PESERA

Scope and aim of the model

Simulation of biophysical processes amongst which hydrology and vegetation dynamics, as well as a number of soil threats.

Main concepts and modelling paradigm

PESERA is a process-based model.

Scale the model has been applied to and can be applied to

The model has so far been applied to regions, countries and continents. De original development of the model was at European level and since it has also been applied to smaller areas.

Is the model spatially explicit?

Yes. The model operates on a grid.

Spatial resolution of the model and flexibility of this resolution

The model has so far been applied to grid cells with a resolution varying between 100 m. and 1000 m.

Does the model include temporal dynamics?

Yes. Temporal dynamics are crucial in the model as results for a time t+1 build on results from time t.

Temporal resolution of the model and flexibility of this resolution

The model works on a monthly resolution.

External drivers included

Main drivers of change when running the model in for future years are changes in climate inputs such as rainfall and PET and land use, crop choice and land management inputs.

Management options included

PESERA includes a set of land management options for farmers and natural land holders.

Indicators calculated

PESERA calculates biophysical indicators such as run-off, infiltration, yield as well as a series of soil threats.

Input data required and desired

- Climata data.
- Soil data.

PESERA requires maps as input. A list of (main) input data is provided below. For many of the input data a separate map is needed for each month, as the time-step is 1 month, and hence the values of input parameters change over the year.

For the equilibrium stage raster maps with per cell: Root depth, Surface roughness, Roughness reduction, Soil water storage capacity, Crusting, Erodibility, Standard deviation of elevation, Land use, Scale depth, Mean rainfall per month, Rain per rainday, Mean temperature per month, Temperature range per month, Coefficient of variation of rainfall per month, Mean potential evapotranspiration, Planting date, Crop map, Soil water availability at 300 mm, Soil water availability at 1000 mm

For the simulation stage raster maps with per cell: Initial sum of soil erosion, Cbarest, Crough, HCStore, Snow melt, Frozen soil, Snow fraction, Snow pack, Vegetation, Humus, Vegetation cover, Land use, Crop map, Planting date, Mean rainfaill per month, Rain per rainday, Mean temperature per month, Temperature range per month, Coefficient of variation of rainfall per month, Mean potential evapotranspiration.

Parameters required and desired

Equilibrium: Effective PET coefficient, Effective freezing coefficient, Effective melt coefficient.

Simulation: Y Prop, Number of integration steps

Data required for calibration and validation

- Run-off data
- Vegetation / yield biomass
- Erosion measurements and measurements for other soil threats

Calibration and validation process

Comparison of simulation results against data and assessment of results by experts.

Outputs

- Run-off (raster files).
- Vegetation biomass and cover (raster files)
- Soil threats: (raster files): water erosion, wind erosion, susceptibility to landslides, loss in organic matter, salinization, nitrate leaching.

Run-time of the model

For Europe in the order of hours-days depending on the resolution.

Availability of model

Yes, PESERA is available without additional costs as part of the project.

Availability of model developer

Yes for the C++ version of PESERA.

Availability of source code

Yes, to the consortium partners.

Programming language

Excel, FORTRAN, C++

Possibility to re-use worldwide

Yes.

Ability to adapt to meet requirements

High.

Common uses in combination with other models

- Integration with Metronamica in DeSurvey and DESMICE in DESIRE.

Potential and limitation for integration with other models

None.

Additional remarks

None.

A2.2. Input data description and sources

Table A2.1 provides an overview of input requirements for the PESERA biophysical model. A total of 104 spatially distributed input maps are needed to run the biophysical model component. The input data can be subdivided into the following categories: (1) topography, (2) climate, (3) soil properties and (4) land use and crop data. Below is explained how the data for each layer of each category was derived.

All maps have a resolution of 500m, and projection ETRS 1989 LAEA (Lambert Azimuthal Equal Area); GCS_ETRS_1989; Datum: D_ETS_1989.

Table A2.1: Overview of PESERA input requirements

Category	**Variable**	**number of maps**	**data source**
Topography	Local relief – st. dev. of elevation	1	ESDAC database (RECARE project)
Climate	Mean monthly temperature	12	E-OBS version 21.0e, at 0.1° spatial resolution and daily scale 1981-2010 (equilibrium run)
	Mean monthly temperature range	12	
	Mean monthly rainfall	12	
	Mean monthly rainfall per rain day	12	
	Coefficient of variation of mean monthly rainfall per rain day	12	
	Mean monthly PET	12	Calculated from monthly Tmean and Trange using Hargreaves et al. (1985) method
Soil properties	Erodibility class (sensitivity to erosion)	1	Classified RUSLE K-factor map by Panagos et al. (2015) https://esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe
	Crusting class (sensitivity to soil surface crusting)	1	Pedotransfer functions based on soil type and texture (ESDB)
	Scale depth (proxy for infiltration)	1	Based on Texture classes (ESDB)
	Soil water available to plants (0 - 300 mm)	1	Pedotransfer functions based on Available Water Content, Texture,

	Soil water available to plants (300-1000 mm)	1	Soil packing density and restriction of soil to bedrock; ESDB and SWAT-HWSD for Iceland and Cyprus
	Effective soil water storage capacity	1	
Land use & crop data	Land use map	1	From Metronamica application
	Crop map	1	
	Planting month (for crops only)	1	Grouped per climate regions (see details below)
	Initial ground cover (%)	12	Following PESERA project manual estimations; adapted where needed
	Initial surface storage (mm)	1	Following PESERA project manual
	Surface storage reduction (%)	1	Following PESERA project manual: 50% for crops, 0% for other land uses
	Rooting depth	1	Combined approach following PESERA project manual, FAO data http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/. and SWAT database.

A2.2.1. Topographic data

One of the main variables in the model is local relief. It is estimated from the Digital Elevation Model (DEM) as the standard deviation of elevation with a circle of 1.5 km (5 cell radius) diameter around each cell. The DEM and derived relief map (Fig. A2.1) were derived from the RECARE project, in which ESDAC DEM data was used.

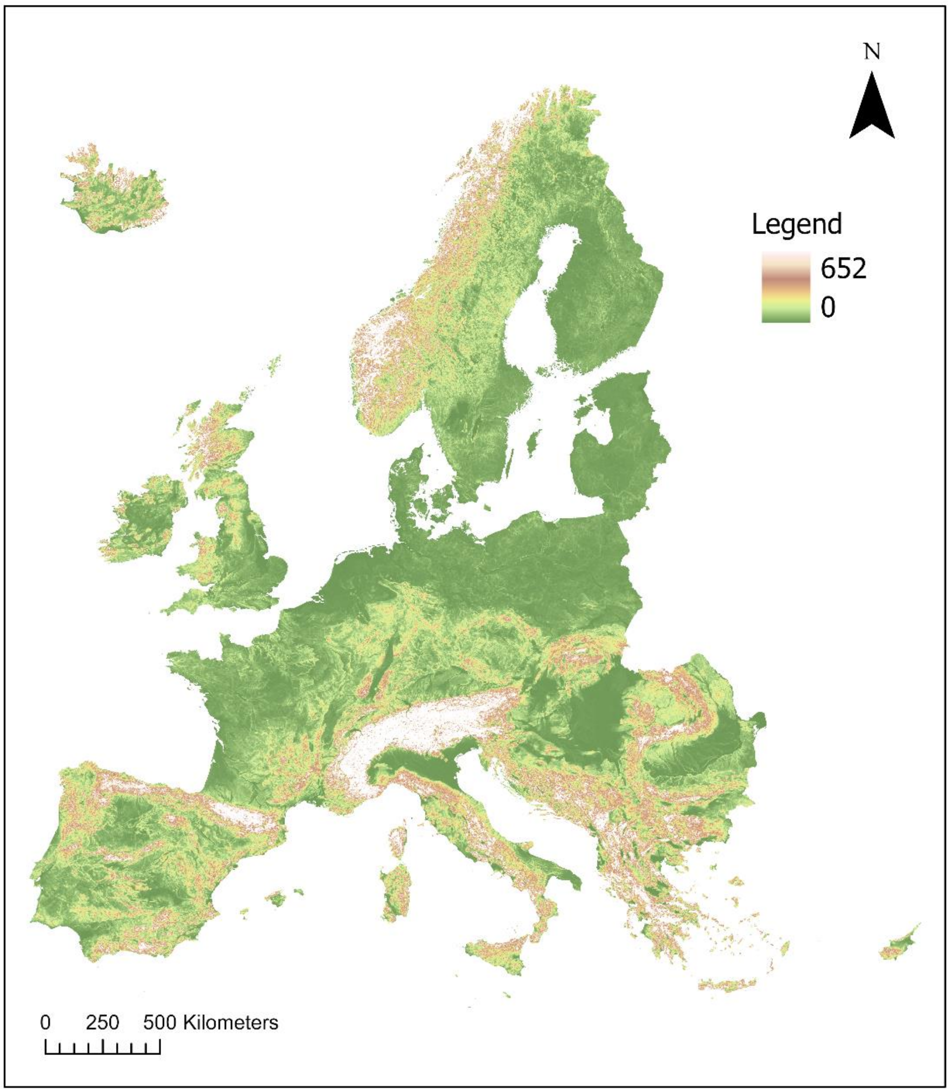

Figure A2.1: Relief map (st dev of elevation in a 1500m radius) for Europe.

A2.2.2. Climate data

Present-day climate data

SoilCare used E-OBS version 21.0e, at 0.1º spatial resolution and daily scale. Daily data for the ensemble mean of mean temperature, minimum temperature, maximum temperature and rainfall were collected for 1981-2010, representing the reference period used to bias-correct climate scenarios. The monthly parameters shown in Table A2.1 were calculated from these values, after being interpolated to a 500m resolution. The data source is Cornes et al. (2018): https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php

Climate Scenarios

To minimize bias in the project, climate scenarios at high resolution (0.1º), and already bias corrected with present-day climate (E-OBS) were used. The considered emission scenarios were RCP4.5 (closer to the average of all emission scenarios) and RCP8.5 (a more extreme emission scenario). The selected GCM-RCM combination was MPI-ES-LR + CCLM4-8-17. This means that we used the MPI-ES-LR GCM, which has a median sensitivity to climate change (Andrews et al., 2012) combined with the CCLM RCM, which appears to have less bias for temperature and rainfall in several European regions (Kotlarski et al., 2014).

We used data from the JRC EU High Resolution and Precipitation dataset, which is already bias-corrected using E-OBS (Dosio, 2016). Data access is here: https://data.jrc.ec.europa.eu/dataset/jrc-liscoast-10011

A2.2.3. Soil properties

Soil property data is used to calculate storage capacity and therefore the runoff threshold, and affects plant growth through soil water availability. Six layers of soil data are required as input, some of which are dynamically updated over time: (1) erodibility, which is the sensitivity of the soil for erosion; (2) crusting, which is the sensitivity of the soil to surface crusting and affects the infiltration, (3) scale depth, which is a proxy for infiltration, (4) the effective soil water storage capacity and (5-6) soil water available to plants for depths 0-300 mm and 300-1000 mm.

Erodibility

The erodibility map is a 5-class map (Fig. A2.2) based on the erodibility K-factor of the RUSLE, as prepared by Panagos et al., (2015b). The data (500m resolution) is available at: https://esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe

In SoilCare, we used the erodibility map with stoniness effects incorporated, as this better represents erodibility in areas with stony soils, such as the Mediterranean. The K-factor values were grouped into 5 classes based on the classes given in Panagos et al. (2015b), but grouped into 5 classes instead of the 8 classes given there (Table A2.2).

Table A2.2: Erodibility classes used in SoilCare erodibility map

Erodibility class SoilCare	K-factor values
1	< 0.02
2	0.02 – 0.028
3	0.028 - 0.038
4	0.038 – 0.046
5	> 0.046

For three countries, exceptions were made: Norway, Sweden and Iceland. In large parts of Iceland, and mountainous parts of Norway and northern Sweden, erodibility was classified as 5 (highest class). Except for bare rock and glacier areas, which were excluded, these areas consist of sparsely vegetated land cover and heather, usually on very thin soils and underlain by granite bedrock closely at the surface. As this bedrock is hardly erodible, combined with our Norwegian partner's observation that these areas produce very clean water (i.e. hardly any erosion), the erodibility classes for these areas were adapted as follows:

- The RUSLE K-factor was recalculated using equation 1 (Panagos et al., 2014):

$$K = [2.1 * 10^{-4} * M^{1.14} * (12 - OM) + 3.25(s - 2) + 2.5(p - 3))/100] * 0.1317 \qquad (1)$$

With M the textural factor (equation 2):

$$M = (m_{silt} + m_{sand}) * (100 - m_{clay}) \qquad (2)$$

With m_{silt} = silt fraction (%), m_{sand} = sand fraction (%) and m_{clay} = clay fraction (%).

OM = the organic matter content (%), s = the soil structure class (1 = very fine granular, 2 = fine granular, 3 = medium or coarse granular, 4 = blocky, platy or massive), p = the permeability class, ranging from 1 = very rapid to 6 = very slow.

Texture (clay, silt, sand fraction) and organic carbon data was derived from SoilGrids. Data on the permeability and structure was obtained from the ESDAC database. For soil structure, the topsoil structure data was used; for permeability the WR data (dominant annual average soil water regime class of the soil profile). Soil structure was converted from Good, Normal, Poor and Humic or Peaty to structure classes 1, 2, 3 and 4 respectively following Panagos et al. (2015). Water regime (WR) classes 0 – 4 were converted to permeability classes 2-5 respectively.

This resulted in a new K-factor map that was classified into erodibility classes 1 to 3

- Based on the Corine Land Classification 2018 map, sparsely vegetated areas (CLC value 32) was given an erodibility of 1 – there areas were observed to be very close to / bordering the bare rock areas. Land use class 'heathland' (CLC value 27) was given an erodibility of 2, as these areas were again bordering the sparsely vegetated areas. Any remaining areas with erodibility classes 4 or 5 were set to a maximum erodibility class 3.

These two maps were finally combined, taking the minimum of both maps. According to feedback from local Norwegian partners, the resulting map would better represent the erodibility in the mountainous areas in Norway and test runs with the PESERA model indeed showed much lower, and more realistic erosion values for these areas.

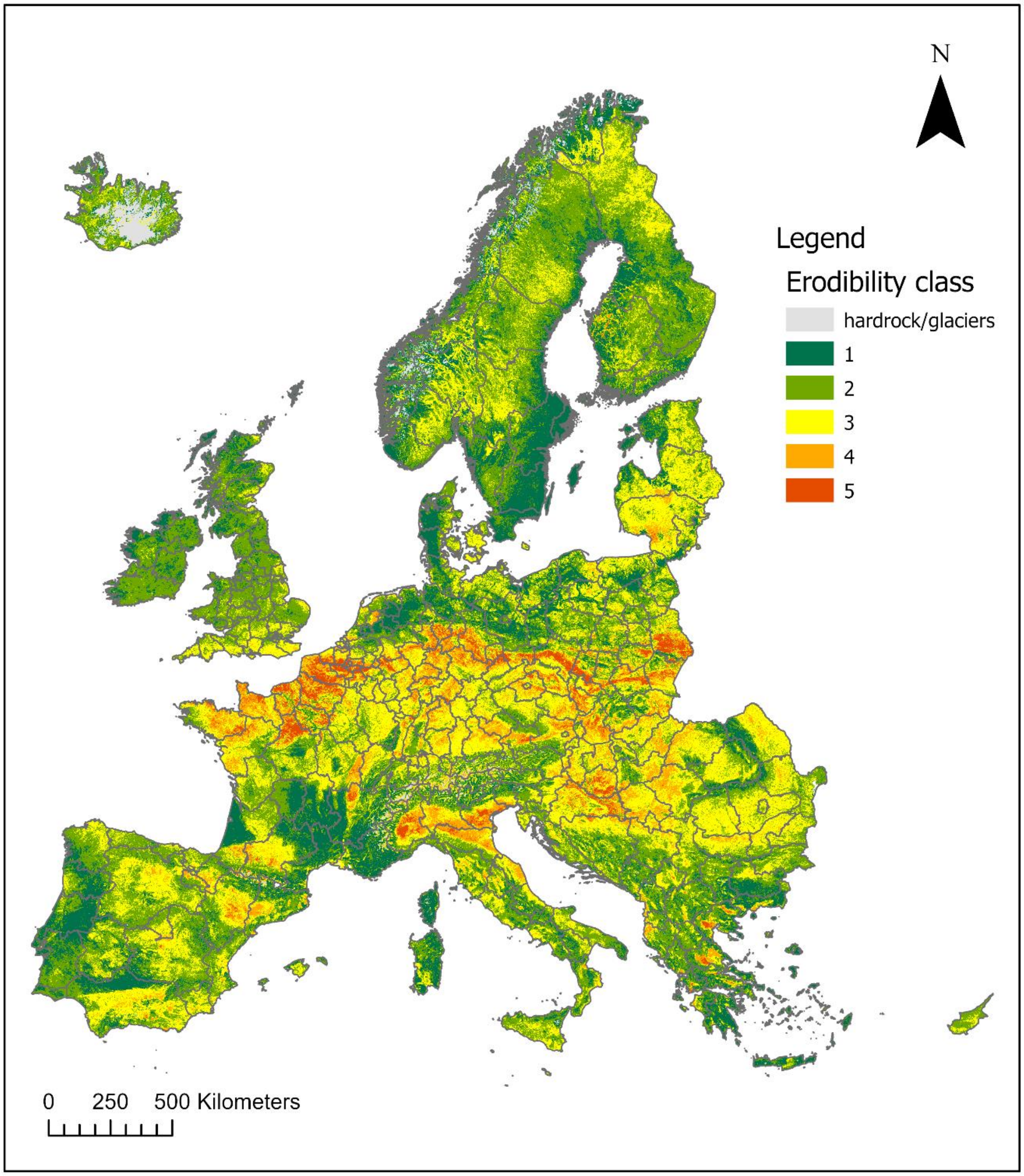

Figure A2.2: Erodibility map. Note that bare rock and glacier areas (based on CLC2018) were excluded (grey colours).

Crusting

The soil sensitivity to crusting index map is shown in Figure A2.3. It was taken from the RECARE project. It is created using pedotransfer functions using texture, parent material and physical-chemical soil properties.

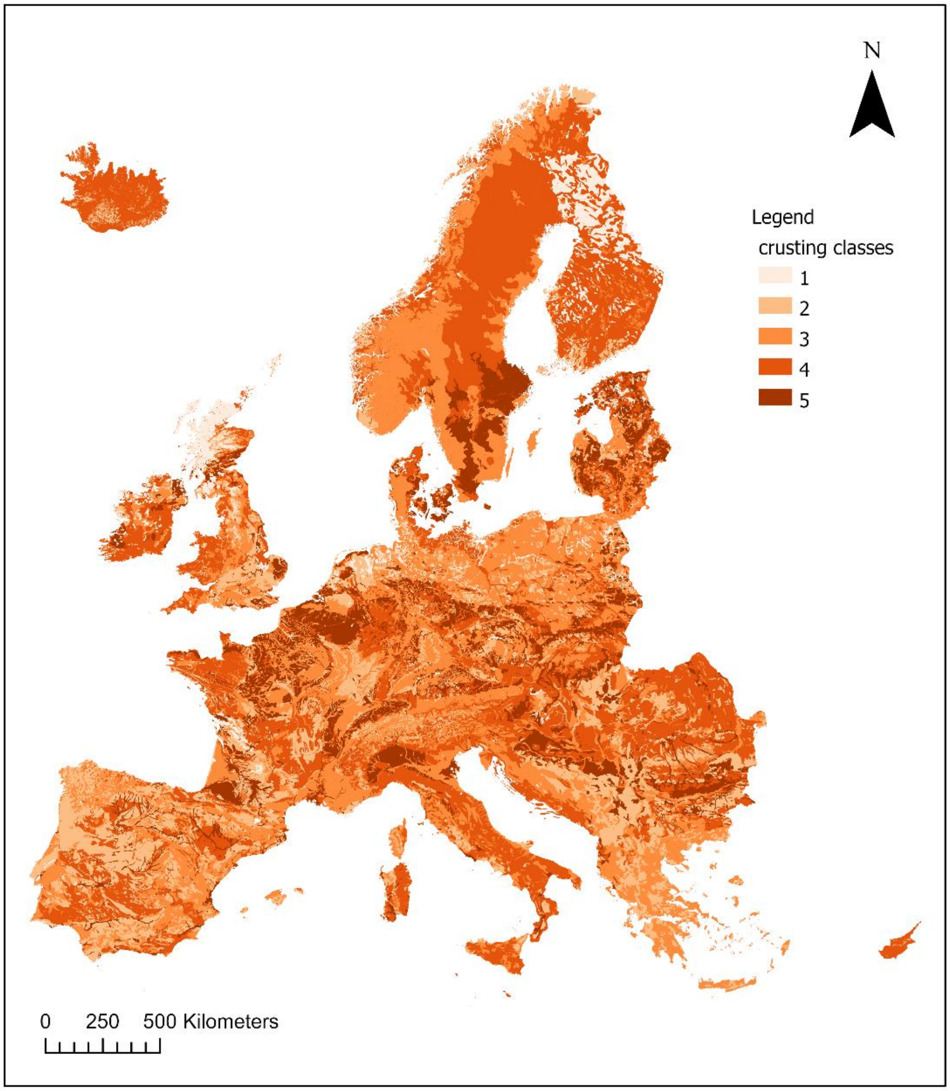

Figure A2.3: Input crusting map for Europe

Scale depth

The scale depth input (Figure A2.4) is derived from soil texture classes (Table A2.3). Texture data was derived from the ESDB database, available at https://esdac.jrc.ec.europa.eu/content/european-soil-database-v2-raster-library-1kmx1km

Table A2.3: Soil Texture and corresponding ZM values (mm)

Soil Texture		ZM (mm)
Coarse	C	30
Fine	F	10
Medium	M	20
Medium Fine	MF	15
Organic Soils	O	10
Very fine	VF	5

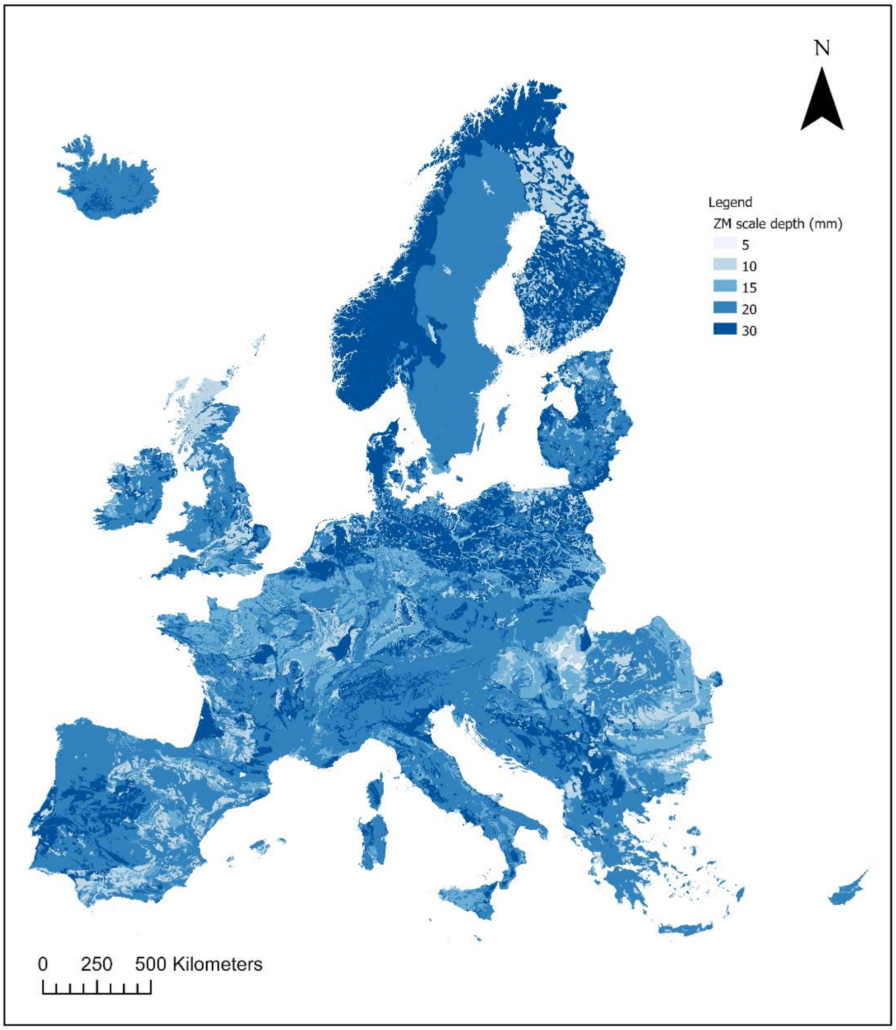

Figure A2.4: ZM scaling depth input map for Europe

Soil water available to plants: 0-30cm (p1xswap1) and 30 – 100 cm (p2xswap2)

Soil water available to plants (both 0-30 and 30-100 cm) and effective soil water storage capacity maps were derived based on the instructions from the PESERA project (Irvine and Kosmas, 2003) and using ESDB data. Available Water Content for topsoil and subsoil (AWC_top and AWC_sub) maps of ESDB were used as a starting point. Additional soil property data used in the pedotransfer functions include texture, packing density and restriction of soil depth by bedrock.

Effective Soil Water Storage Capacity

The effective soil water storage capacity (Figure A2.5) is then calculated from the soil water available to plants in the top- and subsoil following the PESERA project instructions (Irvine and Kosmas, 2003).

Note that estimations for Iceland and Cyprus, that are not included in the ESDB maps, were derived using the SWAT data in combination with the FAO Harmonized World Soil Database (HWSD), available at https://doi.pangaea.de/10.1594/PANGAEA.901309

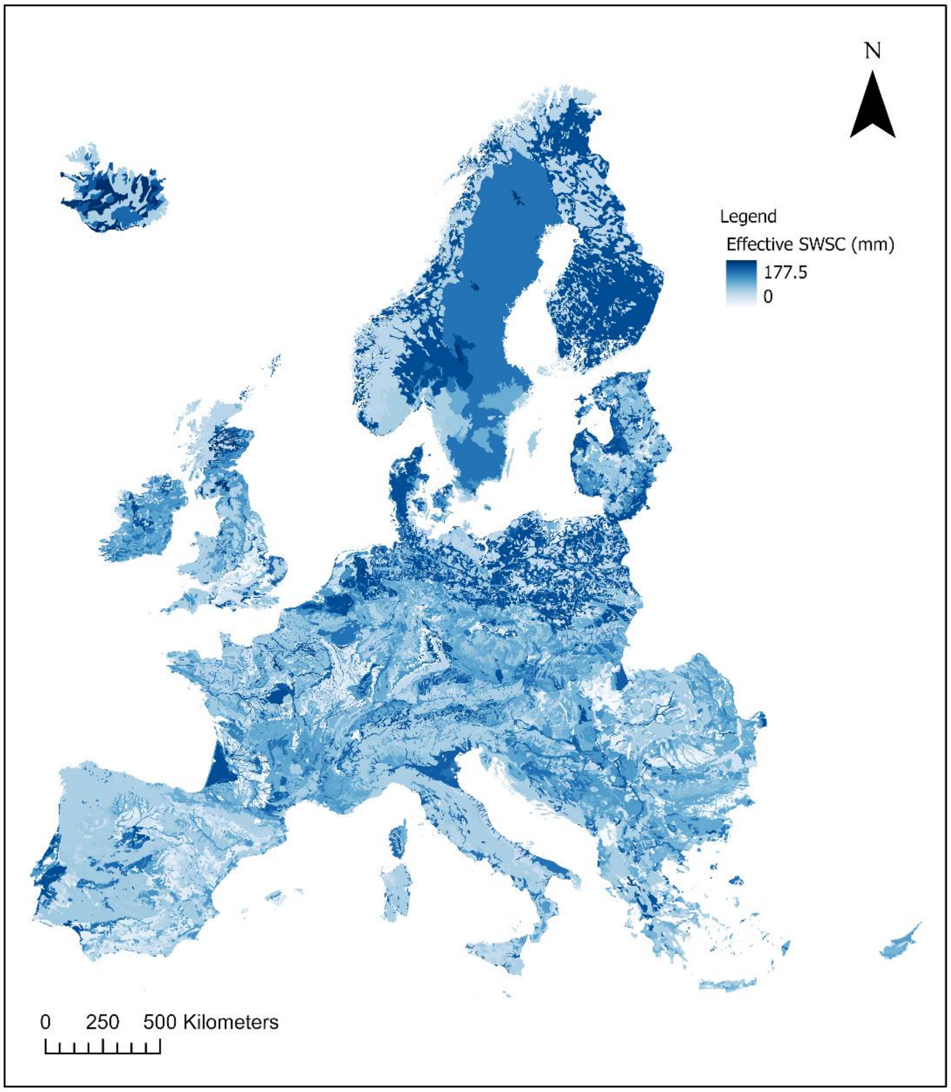

Figure A2.5: Effective soil water storage capacity or Europe

A2.2.4. Land use and crop data

The land use and crop map for Europe were derived from the Metronamica application (see Annex 1). Further land use and crop data input requirements include rooting depth, initial surface storage, surface roughness reduction per month, groundcover for the permanent crops / land uses, planting month for annual crops, as well as tables with cover and water use efficiency (WUE) values for each crop.

Crop calendars: planting month, wue & cover

As crop calendars for the same crop may differ per climatic region, we created four major agro-climatic regions in Europe, for which crop calendars were constructed for each crop. We did not use existing maps for cropping calendars, as they are either too coarse (Sacks et al. 2010, which includes mean planting and harvest day per crop; Figure A2.6), not crop-specific (Rötzer and Chmielewski, 2001), or represent related variables which are difficult to translate into planting month (Brunel et al., 2013; Gloning et al. 2013). We decided instead to aggregate countries per climatic region. The existing Köppen-Geiger system determines 19 different climate types in Europe. These were aggregated into the four most representative classes, each occupying at least 5% of the SoilCare study area, and together occupying 92% of the total; the remainder were assigned to the closest climate class. It should be noted that the division between climate regions is not clear, and there are often climatic gradients. The six classes were then transformed into four classes with two further aggregations:

- for cropping purposes, the Dry climate regions are similar to the Mediterranean climate regions, so they were reclassified as the latter;
- Polar climate is important in a large part of mountain regions, but agriculture is not practiced there, so for the model they were reclassified as Subarctic climate.

Figure A2.6 shows the climate zones map used for SoilCare:

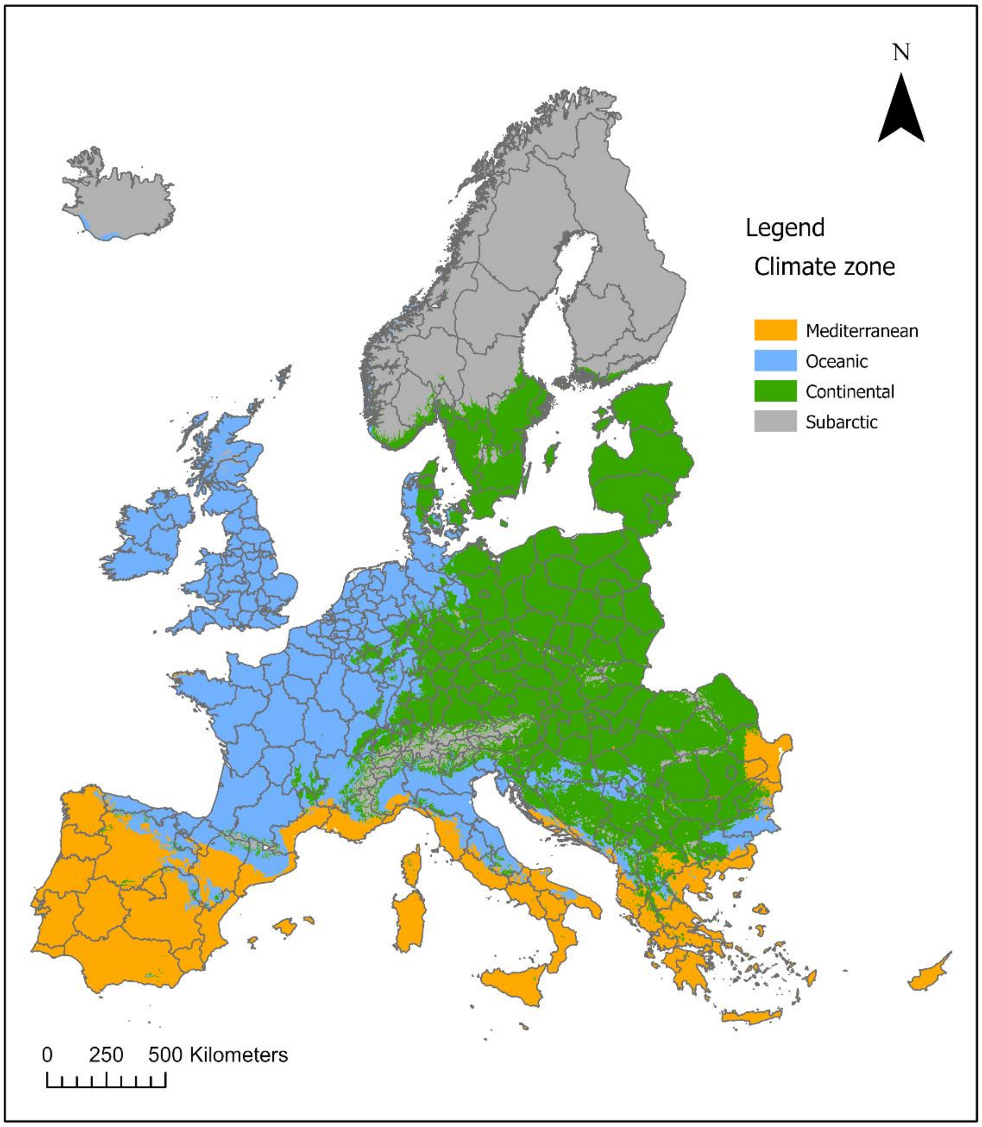

Figure A2.6: Climate zones as used in SoilCare to vary crop calendars by agroclimatic zone

Finally, we chose to aggregate existing crop calendar information for different countries in Europe for four regions: Mediterranean, Oceanic, Continental and Subarctic. We firstly compiled crop calendars per country (with many gaps), and aggregated them using the following datasets according to the dominant climate in the country, in decreasing order of preference:

a) JRC crop calendars for winter wheat, grain maize and rice: https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=sd (scroll down to 'crop calendar')

b) USDA crop calendars for Europe:
https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx and
https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=E4

c) Boons-Prins et al. (1993) with crop calendars for many crops in Europe:
https://edepot.wur.nl/308997

When extended (>1 month) planting and harvesting dates were given, the latest planting and earliest harvesting date were chosen. The aggregation of calendars gave consistent planting and harvest dates for each region, with the Mediterranean region showing large differences from the 3 other regions, either in earlier planting dates or shorter growing seasons. Cropping calendars were discussed with local partners from SoilCare and adapted according to their experience.

Monthly ground cover (%) for each crop was derived mostly from the PESERA project manual (p.11), with some exceptions / additions:

- Sugarbeet: estimated / adapted from potato
- Oilseed: estimates based on pictures in Corlouer et al., 2019 and comparison with winter wheat
- Rice: taken from FAO http://www.fao.org/docrep/S2022E/s2022e07.htm

These cover calendars were then adjusted to the crop calendars. In most cases, the cover calendars fit inside the planting and harvest dates. When they did not fit, they were adjusted to keep the same shape as the PESERA growth curves but fitting a shorter or longer interval as needed. When the crop calendars indicated planting or harvesting seasons longer than one month, the growth curves were extended by repeating the first or last month value (respectively).

Table A2.4 shows the crop calendars per agroclimatic zone and crop, with the cover indicated as value. Dark green cells indicate the start of the growing season (planting month), orange cells indicate the last month of the growing season.

Table A2.4: Crop calendar and ground cover values used in SoilCare for various crops and agro-climatic zones

		Y1												Y2							
crop	**Agroclimatic zone**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Spring cereal	Continental					10	50	90	95	40											
	Mediterranean				10	50	90	95	40												
	Oceanic				10	50	90	95	40												
	Subarctic					10	50	90	95	40											
Winter cereal	Continental										5	5	25	50	75	90	95	95	85	30	
	Mediterranean											5	35	60	80	90	95	90	30		
	Oceanic										5	5	25	50	75	90	95	95	85	30	
	Subarctic										5	5	10	15	25	50	75	90	95	90	30
Maize	Continental				20	50	75	95	95	40	10										
	Mediterranean				20	60	95	95	40												
	Oceanic				20	50	75	95	95	40	10										
	Subarctic																				
Pulses	Continental			20	65	95	70														
	Mediterranean												20	65	95	70					
	Oceanic			20	65	95	70														
	Subarctic																				
Sugarbeet	Continental				10	50	70	90	95	85	50										
	Mediterranean			10	35	60	75	90	95	85	50										
	Oceanic				10	50	70	90	95	85	50										
	Subarctic																				
Potato	Continental				10	70	95	95	85	35	10										
	Mediterranean				10	70	95	95	85	35											
	Oceanic				10	70	95	95	85	35	10										
	Subarctic				10	70	95	95	85	35	10										
Oilseed	Continental									10	50	80	90	90	90	95	95	85	50		
	Mediterranean											5	35	60	80	90	95	90	30		
	Oceanic									10	50	80	90	90	90	95	95	85	50	50	
	Subarctic										10	50	80	90	90	90	95	90	50		
Veg & Flowers (sunflowers)	Continental					10	75	95	30												
	Mediterranean				10	65	80	95	30												
	Oceanic					10	75	95	30												
	Subarctic																				
Rice	Continental					10	40	65	85	90	60										
	Mediterranean					10	40	65	85	90	60										
	Oceanic					10	40	65	85	90	60										
	Subarctic																				
Forage	Continental			10	65	70	70	75	80	70	50										
	Mediterranean												10	70	70	80	50				
	Oceanic			10	65	70	70	75	80	70	50										
	Subarctic																				

Water Use Efficiency were calculated for different crops with the following sources:

- For spring wheat, winter wheat, potato, sugarbeet, sunflower/tomato, bean (pulses): FAO http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/
- For consumption maize (sweet maize) and fodder maize (grain maize): FAO http://www.fao.org/3/S2022E/s2022e07.htm

- For oilseed (winter oilseed rape):
    - Length of the growing stages: Marjanovic-Jeromela et al., 2019: https://www.mdpi.com/2073-4395/9/9/517
    - Kc values: Fig2 in suppl of Corlouer et al., 2019: https://www.mdpi.com/2073-4395/9/12/798/htm
- For rice: FAO paddy rice: http://www.fao.org/3/S2022E/s2022e07.htm

For forage: taken from PESERA manual (Irvine and Kosmas, 2003).

WUE calendars were also based on planting and harvest dates, and used the same method as that for cover calendars, including stretching or shortening curves to match planting and harvesting dates (Table A2.5).

An additional change was to consider irrigation per crop according to climate region. Rice was always considered to be irrigated; in Mediterranean climates, Maize, Sugarbeet, Potatoes and Veg & Flowers were considered to be irrigated when soil water deficit is above 0.3.

Table A2.5: Crop calendar and water use efficiency values used in SoilCare for various crops and agro-climatic zones

		Y1												Y2							
crop	**Region**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Spring cereal	Continental					0.3	0.6	1.15	1.15	0.3											
	Mediterranean				0.3	0.6	1.15	1.15	0.3												
	Oceanic				0.3	0.6	1.15	1.15	0.3												
	Subarctic					0.3	0.6	1.15	1.15	0.3											
Winter cereal	Continental										0.3	0.3	0.4	0.6	0.8	1	1.15	0.6	0.4	0.3	
	Mediterranean											0.3	0.5	0.7	0.9	1	1.15	0.5	0.3		
	Oceanic										0.3	0.3	0.4	0.6	0.8	1	1.15	0.6	0.4	0.3	
	Subarctic										0.3	0.3	0.3	0.3	0.4	0.6	0.8	1.1	0.6	0.3	0.3
Maize	Continental				0.4	0.7	0.95	1.15	1.15	0.7	0.2										
	Mediterranean				0.4	0.8	1.15	1.15	0.7												
	Oceanic				0.4	0.7	0.95	1.15	1.15	0.7	0.2										
	Subarctic																				
Pulses	Continental			0.4	0.8	1.15	0.35														
	Mediterranean												0.4	0.8	1.15	0.35					
	Oceanic			0.4	0.8	1.15	0.35														
	Subarctic																				
Sugarbeet	Continental				0.4	0.6	0.9	1.2	1.2	0.7	0.5										
	Mediterranean			0.4	0.5	0.7	0.95	1.2	1.2	0.7	0.5										
	Oceanic				0.4	0.6	0.9	1.2	1.2	0.7	0.5										
	Subarctic																				
Potato	Continental				0.5	0.8	1.15	1.15	0.5	0.3	0.1										
	Mediterranean				0.5	0.8	1.15	1.15	0.5	0.3											
	Oceanic				0.5	0.8	1.15	1.15	0.5	0.3	0.1										
	Subarctic				0.5	0.8	1.15	1.15	0.5	0.3											
Oilseed	Continental									0.7	1	1	1	1	1	1	1.15	0.8	0.5		
	Mediterranean											0.7	1	1	1	1	1.15	0.8	0.5		
	Oceanic									0.7	1	1	1	1	1	1	1.15	0.8	0.5	0.5	
	Subarctic										0.7	1	1	1	1	1	1.15	0.8	0.5		
Veg & Flowers (sunflowers)	Continental					0.45	0.9	1	0.7												
	Mediterranean				0.5	0.8	1	1	0.7												
	Oceanic					0.45	0.9	1	0.7												
	Subarctic																				
Rice	Continental					1.1	1.1	1.15	1.2	1.2	0.9										
	Mediterranean					1.1	1.1	1.15	1.2	1.2	0.9										
	Oceanic					1.1	1.1	1.15	1.2	1.2	0.9										
	Subarctic																				
Forage	Continental			0.4	0.8	0.8	0.8	0.9	0.9	0.8	0.6										
	Mediterranean												0.4	0.8	0.8	0.9	0.6				
	Oceanic			0.4	0.8	0.8	0.8	0.9	0.9	0.8	0.6										
	Subarctic																				

Ground cover for permanent crops

Monthly canopy cover for permanent crops (Table A2.6) are based on the PESERA project estimations (Irvine and Kosmas, 2003):

Table A2.6: Monthly canopy cover estimates used in SoilCare.

Land use	**Month**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Artificial, water	100	100	100	100	100	100	100	100	100	100	100	100
Bare land	0	0	0	0	0	0	0	0	0	0	0	0
Grassland	100	100	100	100	100	100	100	100	100	100	100	100
Shrubs	30	30	30	30	30	30	30	30	30	30	30	30
Vineyards	10	10	10	20	25	30	30	30	30	20	15	15
Fruit trees	10	10	10	20	25	30	30	30	30	20	15	15
Olive groves	10	10	10	20	25	30	30	30	30	20	15	15
Forest (all types)	100	100	100	100	100	100	100	100	100	100	100	100

Initial surface storage, storage reduction and rooting depth

Root depth was estimated based on three sources: the PESERA project manual (Irvine and Kosmas, 2003); estimates from FAO: http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/. These estimates start at 30cm root depth going to 1000 cm at the end of the growing season. As PESERA estimates were lower, a conservative estimate was taken and cross-checked with the SWAT database, which also estimates slightly deeper (maximum) rooting depths. Table A2.7 shows the rooting depths used in SoilCare. For initial surface storage (either 0, 5, or 10 mm) and reduction of surface storage (either 0 or 50 %), the PESERA project manual was followed.

Table A2.7: Rooting depth, initial surface storage and reduction of surface roughness values per land use and crop type

Land use / crop	Rooting depth (mm)	Initial surface storage (mm)	Reduction of surface roughness (%)
Artificial	10	0	0
Bare land	10	5	0
Grassland	500	5	0
Shrubs	600	5	0
Vineyards	800	5	0
Fruit trees	800	5	0
Olive groves	800	5	0
Broadleaf Forest	1000	5	0
Coniferous Forest	1000	5	0
Mixed Forest	1000	5	0
Water	10	0	0
Winter cereals	400	10	50
Spring cereals	400	10	50
Consumption maize	600	10	50
Fodder maize	600	10	50
Pulses	400	10	50
Rice	500	10	50
Sugarbeet	500	10	50
Potato	500	10	50
Oilseed	400	10	50
Vegetables & Flowers	600	10	50
Forage	400	10	50
Fallow	10	10	50

Moreover, and similarly to Mediterranean crops, Mediterranean fruit trees and olive groves were considered to be irrigated when soil water deficit is above 0.3.

A2.3. Parameterization, tuning and performance assessment

The PESERA model was initiated with the input data as described in section A2.2. The model has two phases: an equilibrium phase in which current, long-term climate data is used as input and a simulation phase that is used to simulate the future scenarios (see section 4). The equilibrium phase model outputs were used for calibration. We focussed on simulated biomass / yield, soil humus content, erosion patterns and, to a lesser extent, runoff and soil water deficit. As it was not possible to calibrate the model for all individual countries due to time limitations, we calibrated the results for a few countries across Europe from various climate zones: Belgium, Crete, Iberia and Slovakia, and in addition Norway for erosion patterns specifically. The spatial patterns were qualitatively assessed on EU scale by comparing them with existing maps from literature.

Parameters for tuning were mainly (1) the biomass conversion factor used in the model to calculate gross primary production; and (2) the decomposition factor used in the model to calculate soil organic matter from plant residues. Both parameters are specific for each crop and land use, but generic for all regions.

A2.3.1. Data used for calibration

The following data was used for calibration and comparison of model output:

Biomass / yield

The model outputs above-ground biomass (in kg/m2; which was converted to ton/ha). As yield data was more readily available for most crops, yield was derived using a harvest index for each crop (Table A2.8).

Table A2.8: Harvest indices used for the modelled crops

Crop	Harvest Index
Spring cereal	0.4
Winter cereal	0.4
Consumption maize	0.5
Fodder maize	0.9
Pulses	0.3
Sugarbeet	2
Potato	0.95
Oilseed	0.3
Rice	0.5
Veg & Flowers	0.3
Forage	0.9

For calibration, crop production data from Eurostat were used, containing yield in ton/ha for many crops and countries: https://ec.europa.eu/eurostat/web/agriculture/data/database (Crop production in EU standard humidity (apro_cpsh1)).

For calibration of the biomass of permanent land uses, the following sources were used:

- Forest biomass: Avitable and Camia (2018) compare different Europe-wide forest biomass maps (Fig. A2.7) and in their supplementary material present mean biomass per country.
- For vineyards, olive trees and fruit trees, very little data was found in terms of above-ground biomass and a range of 30 – 50 t/ha was used for calibration

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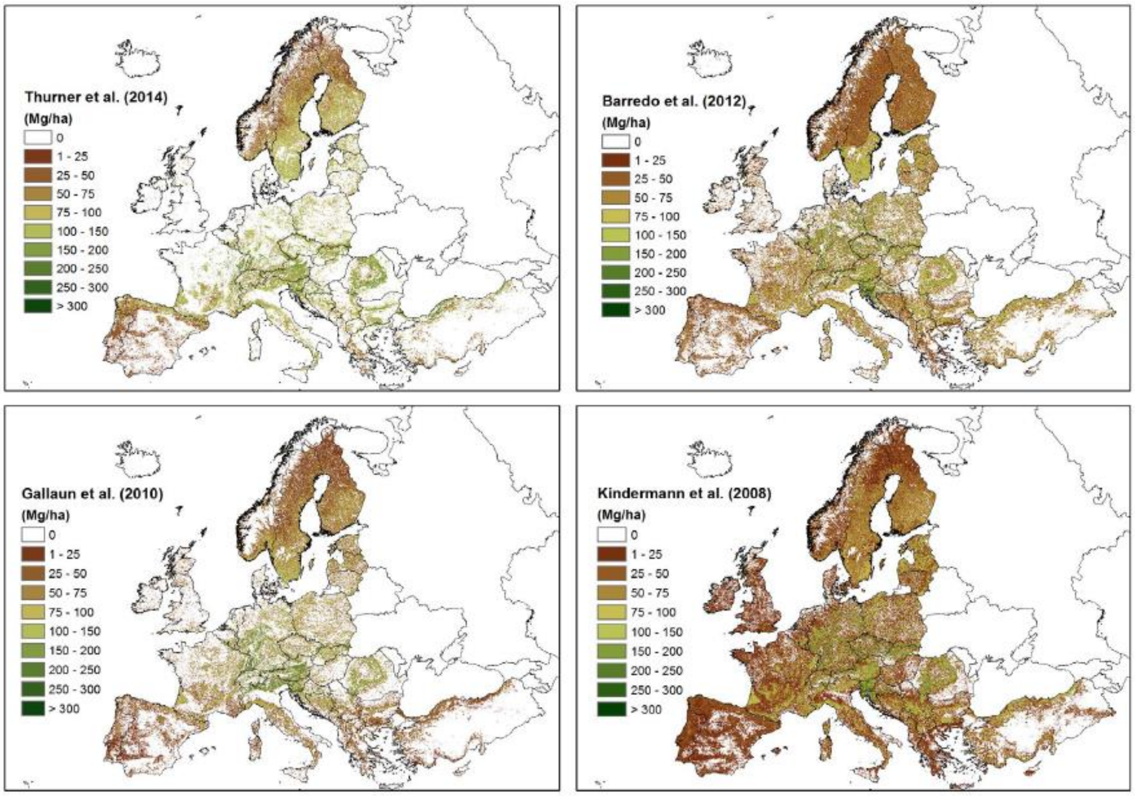


Fig. 2. The four biomass maps for Europe: Thurner, Barredo, Kindermann and Gallaun (clockwise, from upper left).

Figure A2.7: Four biomass maps for Europe, from Avitable and Camia (2018)

Soil organic matter

For soil organic matter the LUCAS topsoil soil organic carbon point data was used: https://esdac.jrc.ec.europa.eu/projects/lucas, which was aggregated to crops and land covers per climate zone (Fig. A2.8).

For general patterns across Europe, several EU-wide maps for SOC / SOM exist (Fig. A2.9-A2.11), which were used to compare the PESERA output SOM with.

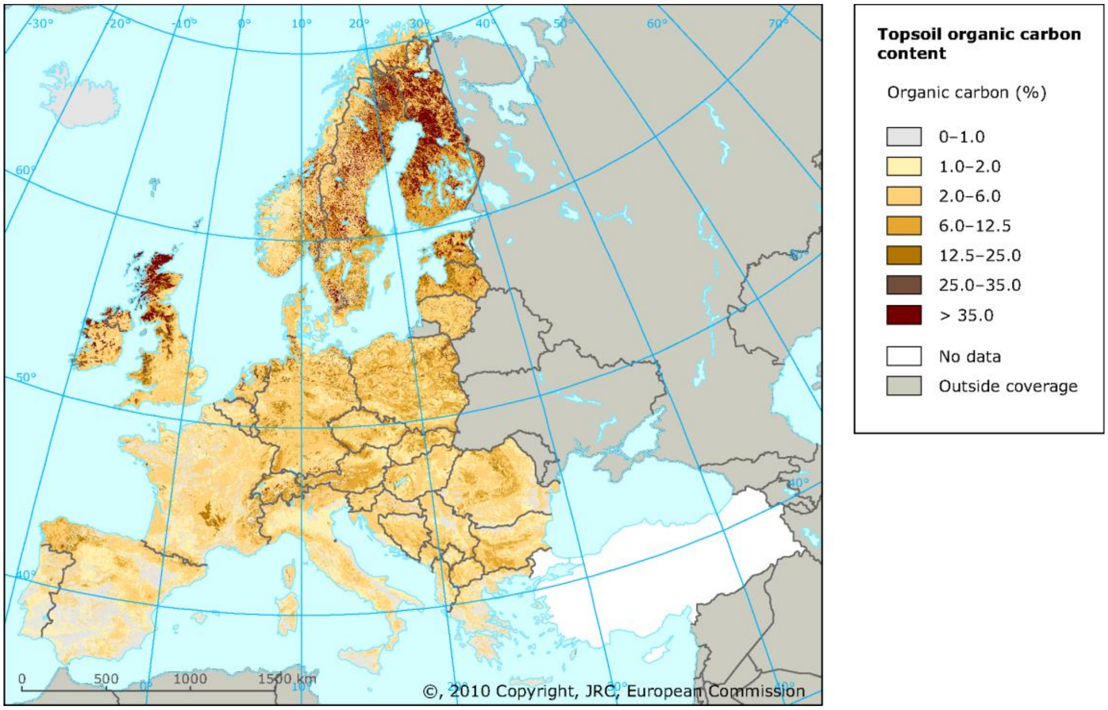


Figure A2.8: European maps of topsoil organic carbon content. Source: https://www.eea.europa.eu/data-and-maps/figures/variations-in-topsoil-organic-carbon

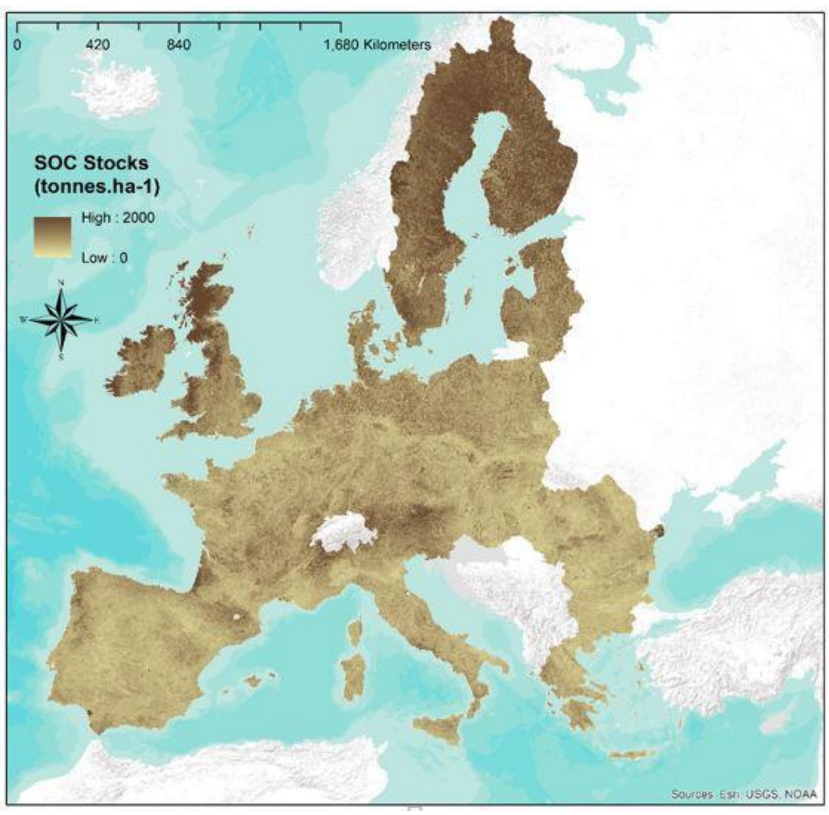


Figure A2.9: EU map of soil SOC stocks. Source: Yigini and Panagos, 2016.

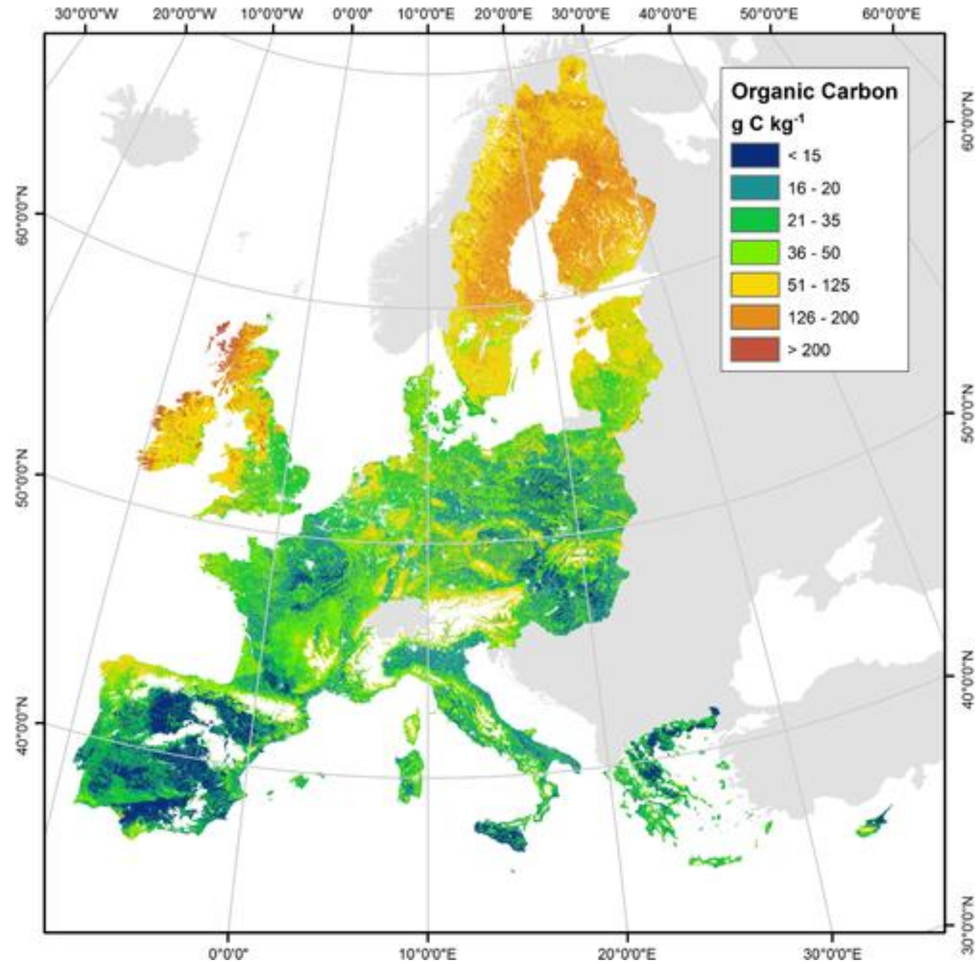


Figure A2.10: EU map of soil SOC stocks. Source: De Brogniez et al., 2015.

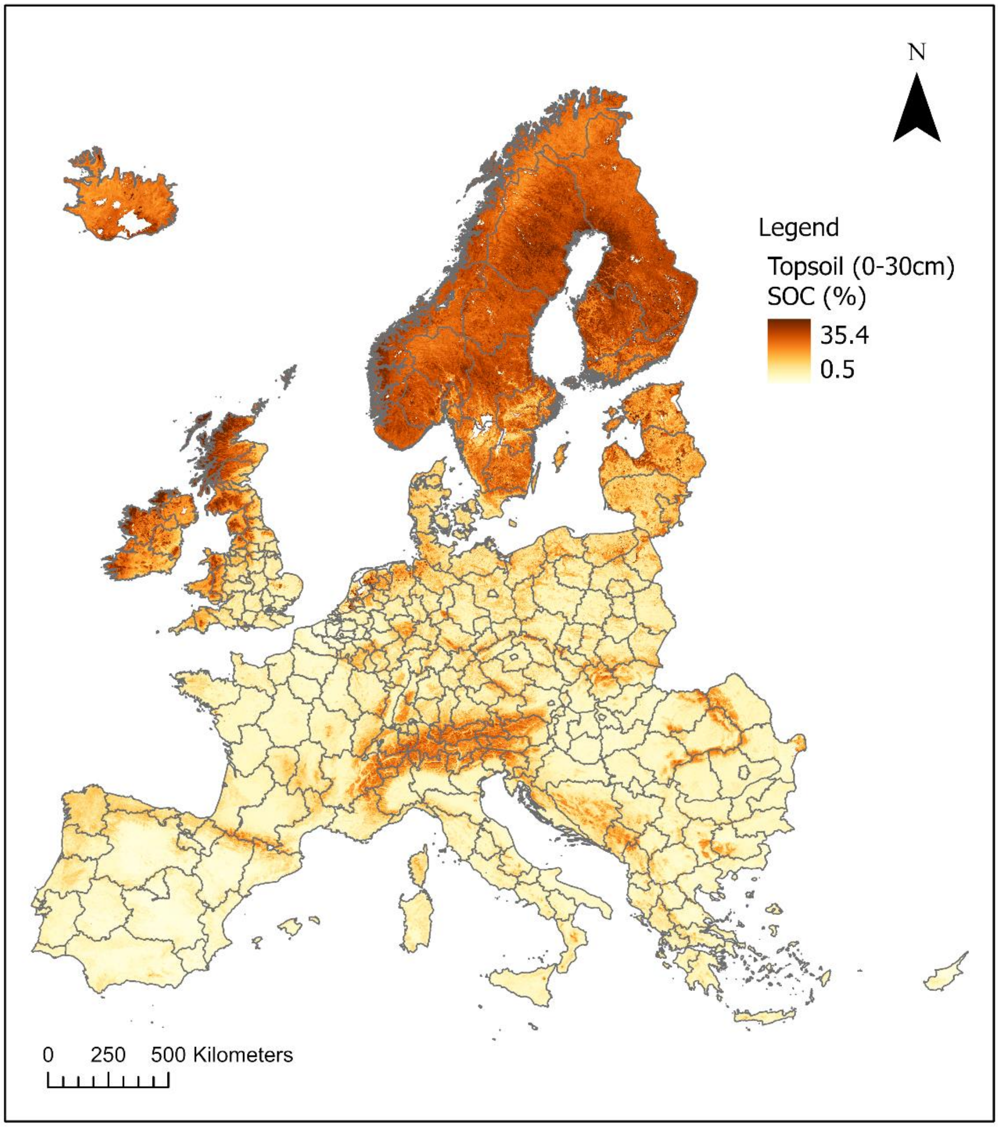


Figure A2.11: Topsoil (0-30cm) SOC content (%). Data source: SoilGrids.

Erosion

For erosion the spatial patterns and average erosion rates per land use / crop were evaluated for some countries by SoilCare partners (see Section A2.3.2 below). The overall spatial patterns were compared with existing soil erosion maps and values from literature:

- Cerdan et al. (2010) synthesized data from erosion plot studies across Europe (Fig. A2.12).

- Estimation of soil loss by Panagos et al., 2015, who used the RUSLE model to estimate soil loss across Europe (Fig. A2.13)

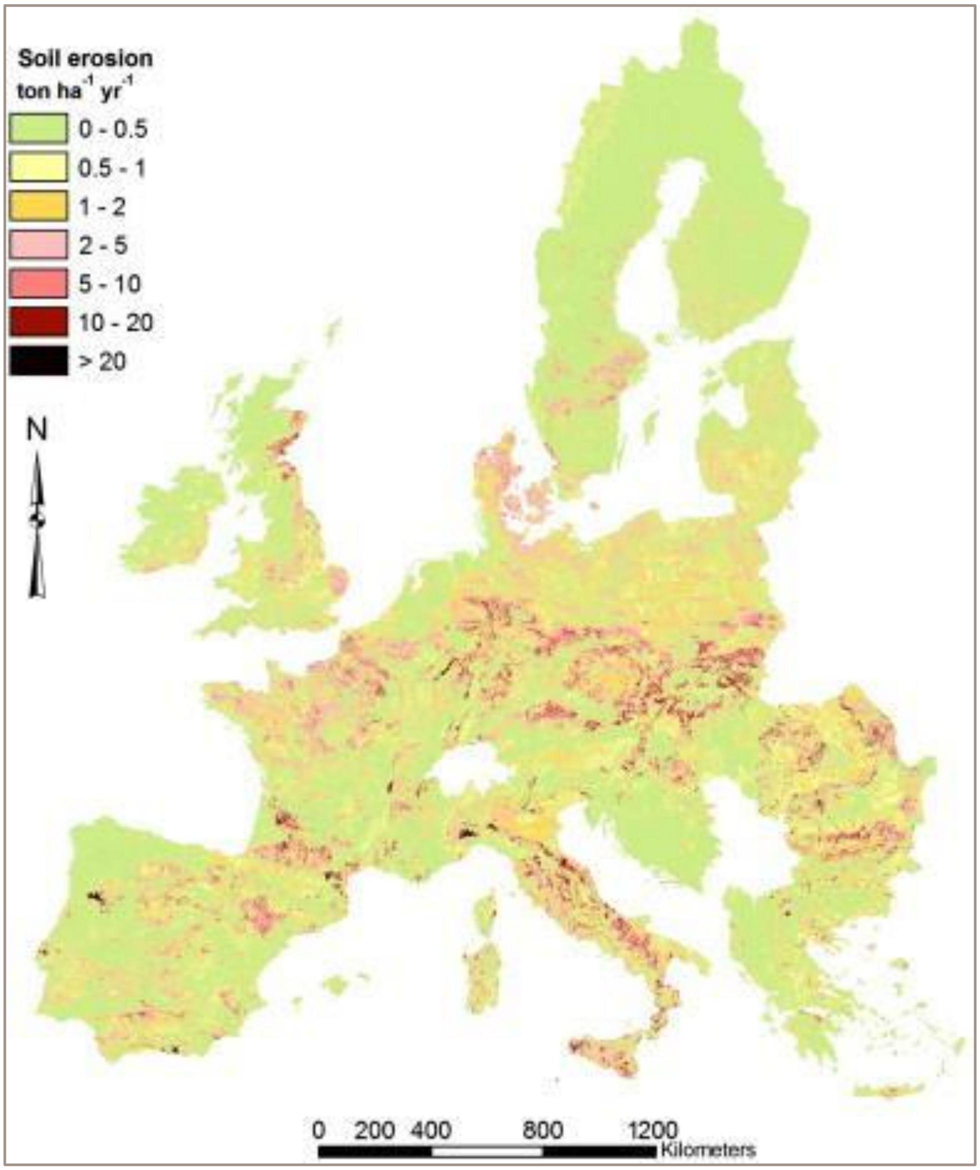


Figure A2.12: Estimated sheet and rill erosion rates calculated for the areas of Europe covered by the CORINE database. Source: Cerdan et al., 2010.

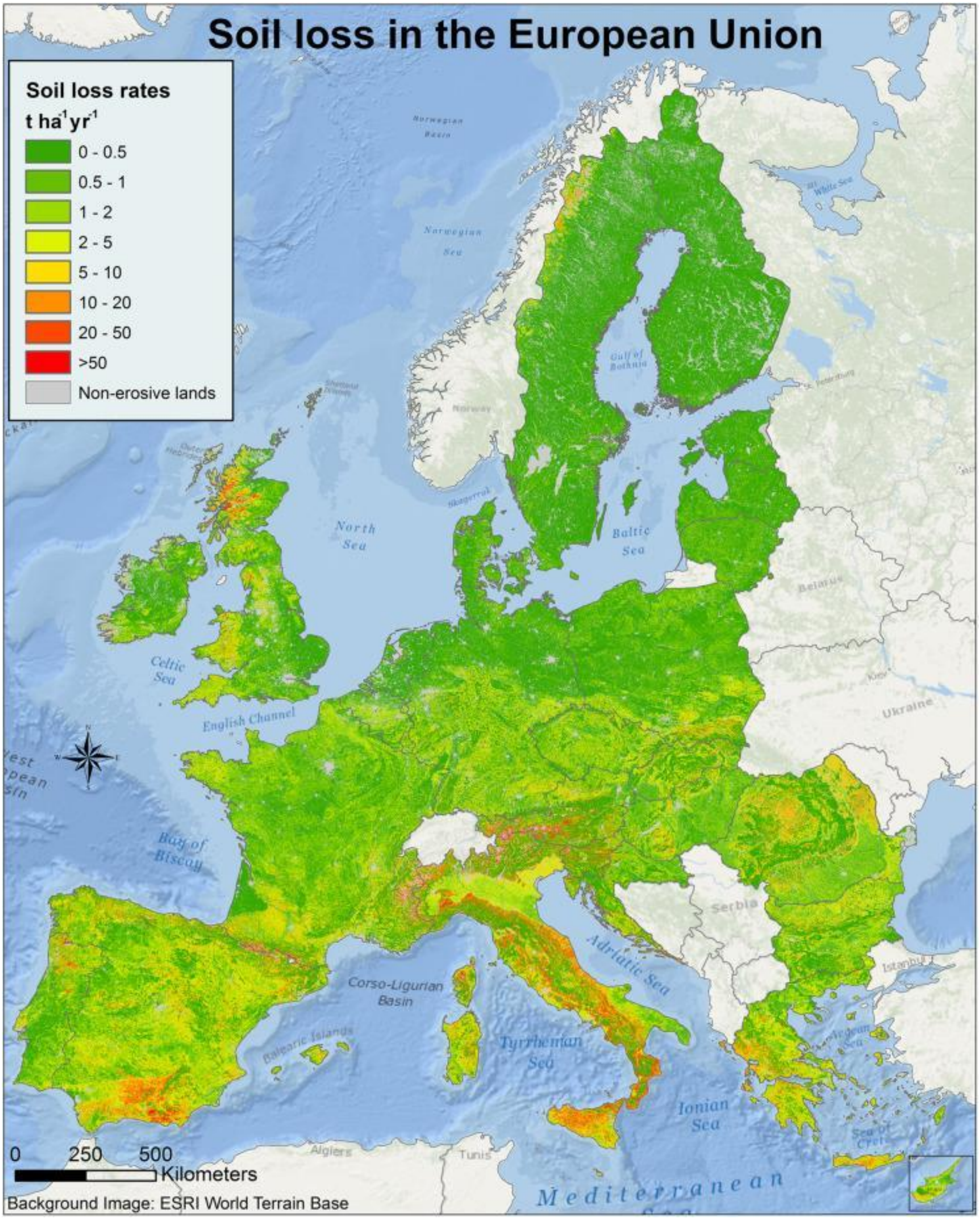


Figure A2.13: Soil loss rates for Europe, based on RUSLE2015 (reference year 2010). Source: Panagos et al., 2015.

A2.3.2. Feedback by partners

To cross-validate and make use of the knowledge of the SoilCare local partners, both the spatial patterns and numerical (aggregated) results were shared with selected countries across Europe and their feedback was used for further fine-tuning. Preliminary results were sent to partners in Belgium, Germany, Greece, Spain, Italy, Norway, Poland and Romania. Based on their feedback:

- The crop calendars were adapted for some crops and regions (Tables A2.4 and A2.5).
- The erodibility map for Norway was adapted because it had too high erodibility in the central mountain areas where soils are very shallow and granite bedrock is very often at the surface; hardly any erosion occurs in these areas. The existing K-factor map from JRC was adapted for certain land uses (following Corine Land Cover 2018):
    - Sparsely vegetated areas were converted to erodibility = 1
    - Heathland was converted to erodibility = 2
    - Other remaining areas with erodibility 4 or 5 were set to erodibility = 3
- Some values for yield of certain crops were adapted and the model was recalibrated slightly to these new values
- Irrigation was added to the baseline scenario in the Mediterranean countries for crops: rice, maize, potato, sugarbeet, vegetables & flowers, fruit trees and olives and for rice in France and Bulgaria.

Furthermore, partners provided national maps useful for calibration, such as the Spanish erosion map and informed us on existing, obligatory practices that are taking place, such as cover crops in Belgium, so that these were included in the baseline scenario already.

A2.3.3. PESERA calibration results using long-term climate

Below, maps of the results of the PESERA baseline with long-term (stable) climate are presented and compared with existing maps and estimates.

<u>Soil Organic Carbon</u>

Fig. A2.14 shows the average SOC content across Europe as calculated by PESERA using long-term average climate input data. The nordic countries (Sweden, Finland) as well as the higher altitude areas clearly show higher SOC values, while lower SOC values are present in Mid-Spain and Eastern Europe. This coincides with the patterns of other SOC estimates (Fig. A2.8-A2.11).

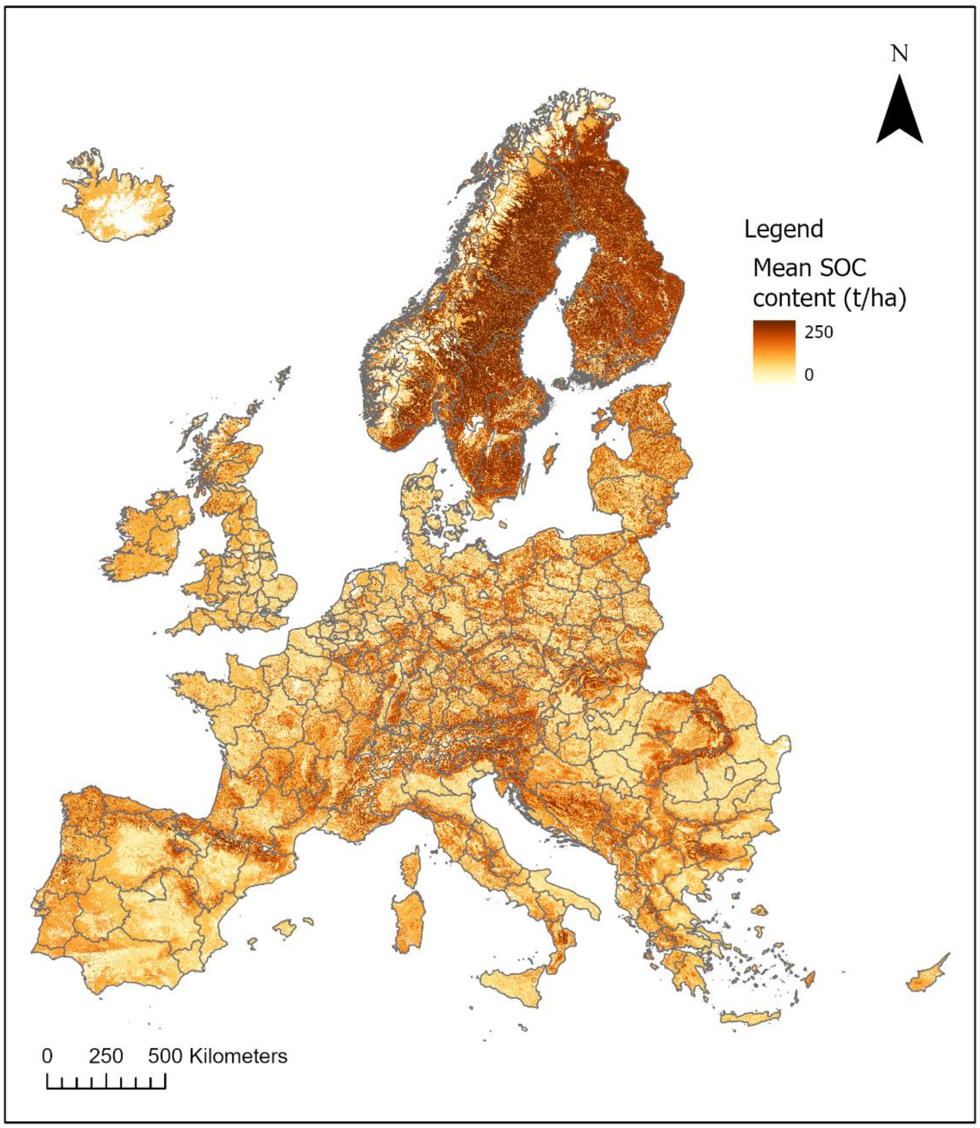


Figure A2.14: Soil Organic Carbon (t/ha) as estimated by PESERA using long-term climate input data.

Above-ground biomass and yield

Figure A2.15 shows above-ground biomass (t/ha) - the maximum of 12 monthly maps was taken - for Europe as estimated by PESERA using long-term climate input data. Areas with high biomass are found in the mountain areas. Note that the legend is the same as used by Avitable and Camia, (2018) (Fig A2.7) for easier comparison. Although difficult to compare, as the maps presented in Avitable and Camia (2018) are not complete, the general pattern coincides. However, the pattern in e.g. the Iberian peninsula seems not to match very well.

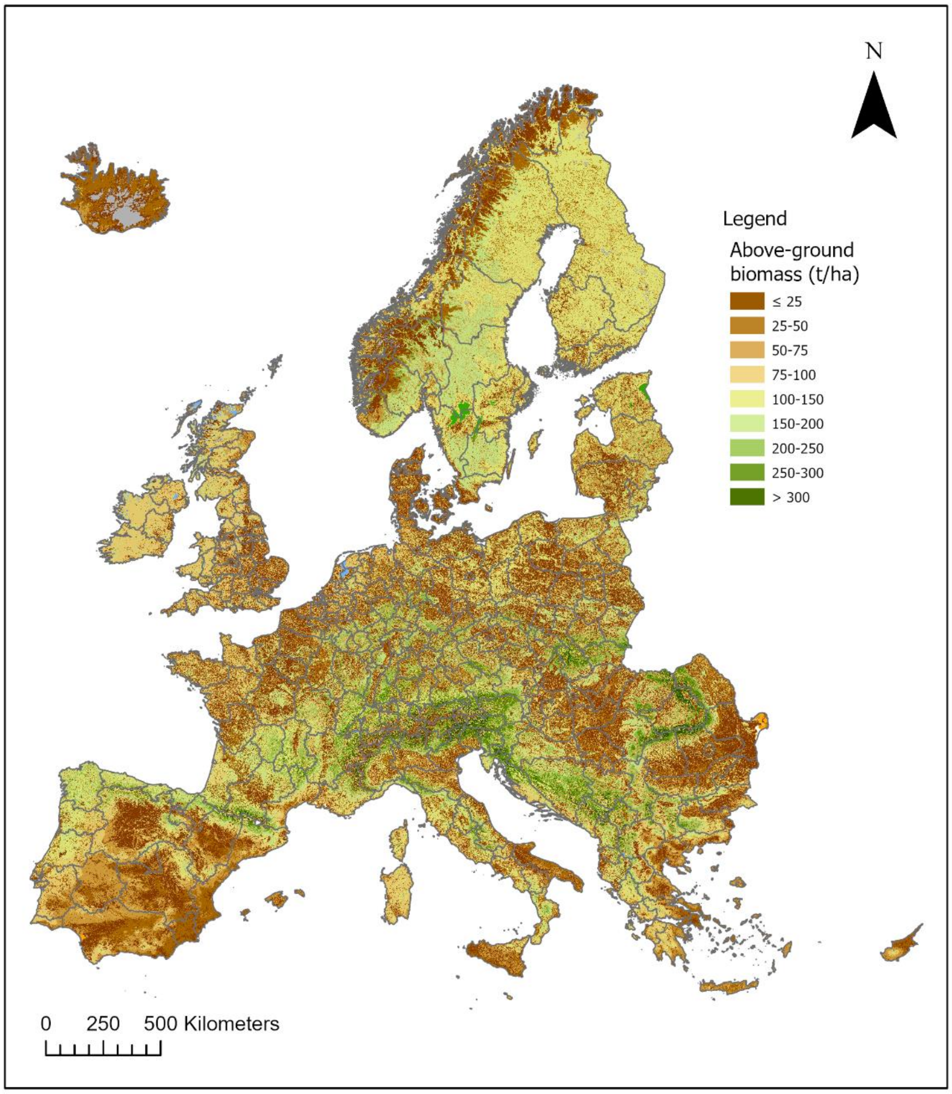


Figure A2.15: Above-ground biomass (maximum of 12 months) as estimated by PESERA using long-term climate input data.

Figure A2.16 shows a spatial map of calculated yields for the annual arable crops (perennial land uses excluded).

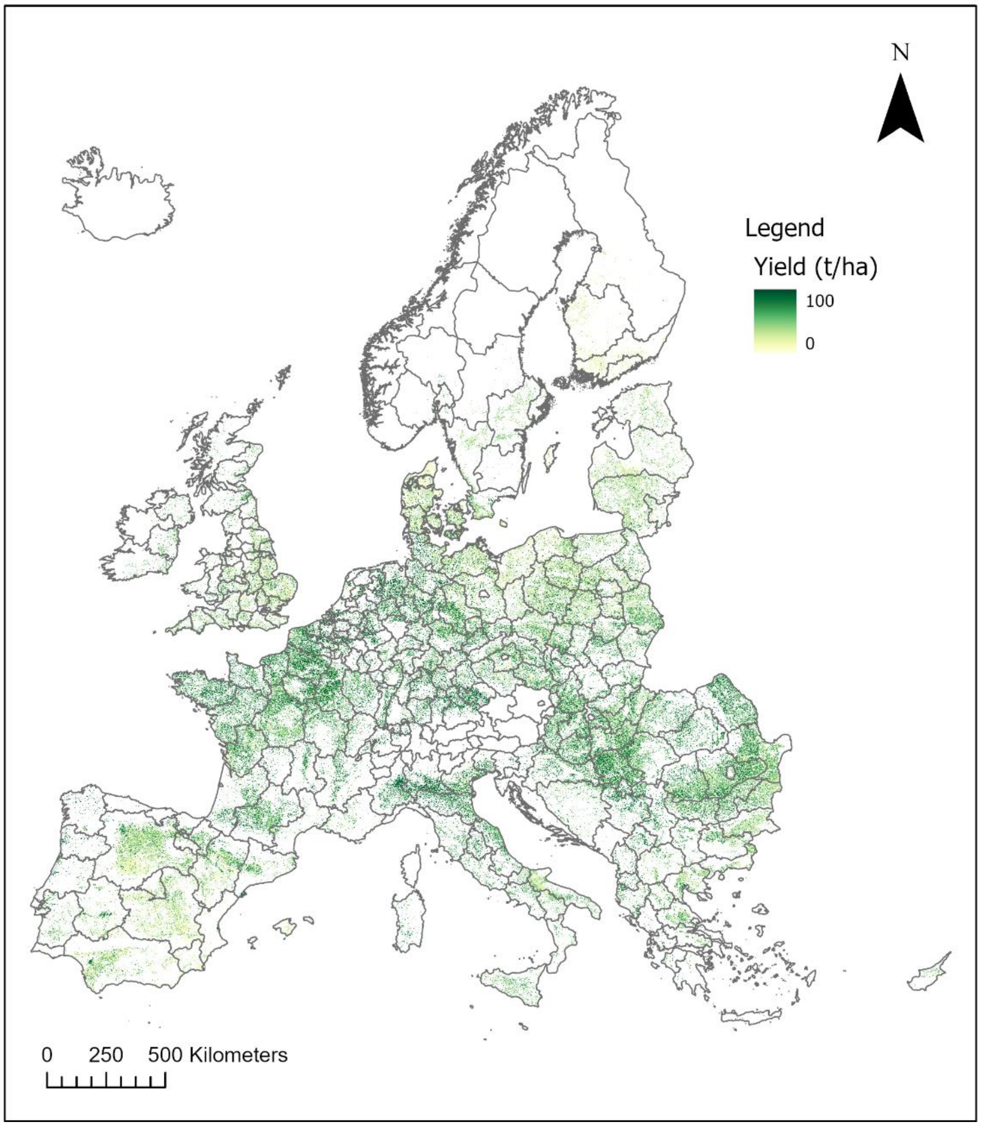


Figure A2.16: Yield for annual arable crops as estimated by the PESERA model using long-term climate input data.

Table A2.9 presents average yield values for the arable crops, calculated by multiplying the biomass by harvest indices (Table A2.8).

Table A2.9: Average yield per crop type across Europe

Crop	Yield (t/ha)
Spring cereals	3.7
Winter cereals	7.5
Consumption maize	10.8
Fodder maize	39.9
Pulses	2.0
Rice	15.9
Sugarbeet	95.6
Potato	37.1
Oilseed	2.9
Vegetables & Flowers	2.9
Forage	19.8

Long-term erosion

Figure A2.17 shows the average yearly erosion as simulated by PESERA using long-term average climate. The mean annual erosion rate as estimated by PESERA was 2.54 t/ha, which coincides well with the estimate by Panagos et al. (2015) of 2.46 t/ha/y for the erosion-prone land covers and 2.22 t/ha/y for all land uses. The general pattern shows relatively high erosion values in the zone from Northern France and Belgium, across Germany and Poland, known as the Loess Belt with soils susceptible to erosion. Also, the mountain areas (Alps, Norway, Apennines, Pyrennees) are visible as areas with high erosion. Note that for especially Norway and the Alps this is partly the consequence of low soil cover (shrubs - 30% cover), which might not represent the local cover very well and lead to an overestimation of erosion. A third area of relatively high erosion is visible in the south of Spain and Italy, where low cover and erodible soils are present. The overall pattern across Europe compares well with estimates using RUSLE2015 (Panagos et al., 2015), who also estimate relatively high erosion in the mountain areas (although Norway and Switzerland are not included in their calculations), in southern Spain and Italy and Northern UK. The RUSLE erosion map predicts less erosion in the Loess Belt than the PESERA estimates. Cerdan et al.'s (2010) estimate of more erosion in the Loess Belt is comparable to the PESERA map. However, in the Cerdan et al., (2010) map, more areas with relatively high erosion are visible, e.g., in Eastern Europe.

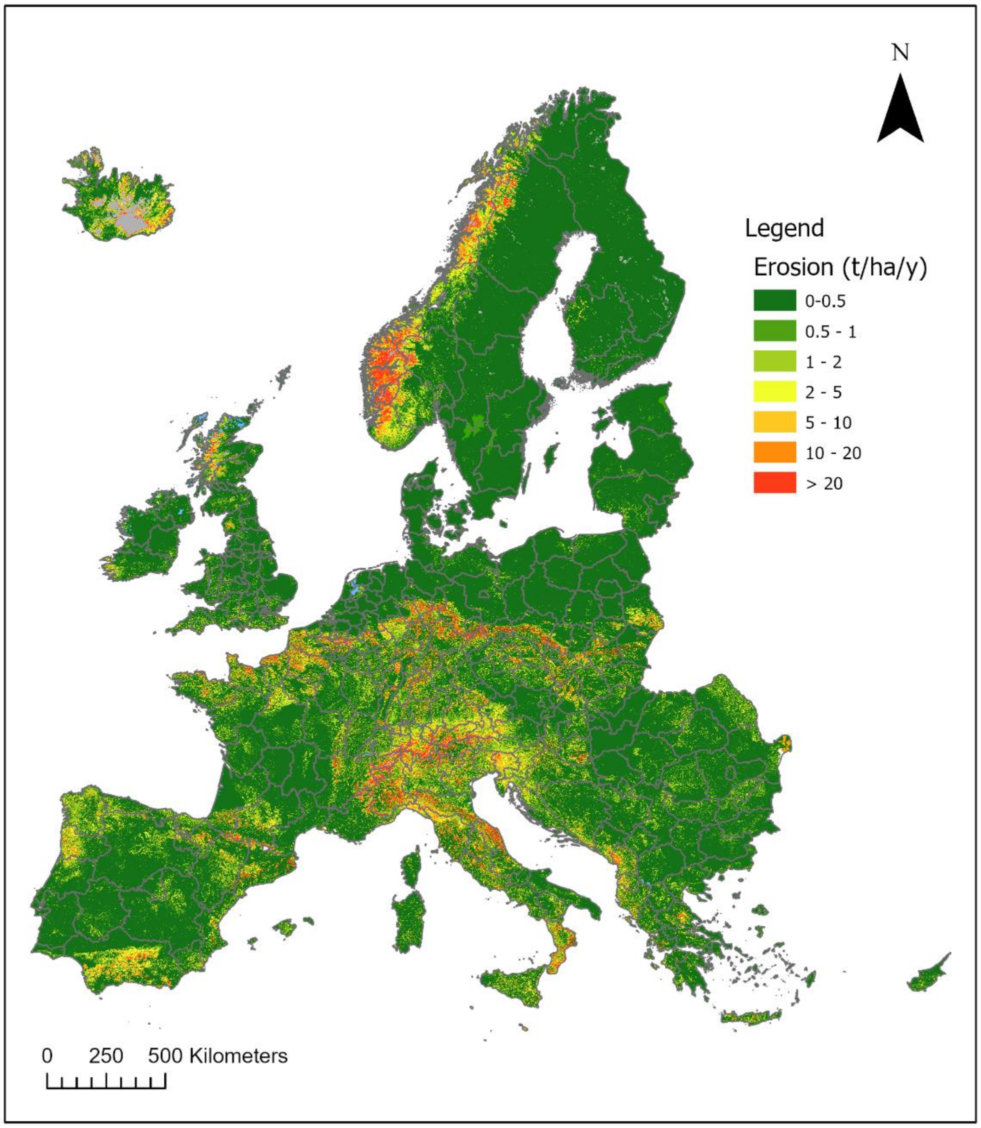


Figure A2.17: Average erosion (t/ha/y) as estimated by PESERA using long-term climate input data.

Table A2.10 lists average erosion values per land use / crop type, across the entire EU. The mean value for arable land of 4.3 t/ha/yr (PESERA) coincides well with the estimate by Cerdan et al. (2010) of 4.4 t/ha/y. Estimated erosion for grassland and forest also coincide, but Pesera estimated much higher erosion for bare soils (probably affected by high erosion values in Norway and the Alps) and lower values for vineyards and orchards.

Table A2.10: Average long-term erosion rates estimated by PESERA per land use and crop type across EU

Land use	**Erosion (t/ha/y)**	**Crop**	**Erosion (t/ha/y)**
Arable	4.3	Spring cereals	2.6
Vineyards	2.8	Winter cereals	4.4
Fruit trees	4.3	Consumption maize	3.9
Olive groves	5.7	Fodder maize	4.3
Grassland	0.4	Pulses	5.1
Broadleaf Forest	0.5	Rice	5.2
Coniferous Forest	0.2	Sugarbeet	11.2
Mixed Forest	0.3	Potato	11.2
Shrubs	1.3	Oilseed	2.9
Bare land	35.2	Vegetables & Flowers	6.9
		Forage	6.7
		Fallow	3.6

Soil water deficit

Fig. A2.18 shows the EU map of soil water deficit for the month August as an example. A clear trend is visible with more deficit in the south (Spain) and south-east (Greece) and less in the higher areas (Alps) and north-eastern Europe (Norway, UK, Ireland). Maps for other months (not shown here) indicate that this trend is aggravated in the summer and much less in e.g. November, as would be expected.

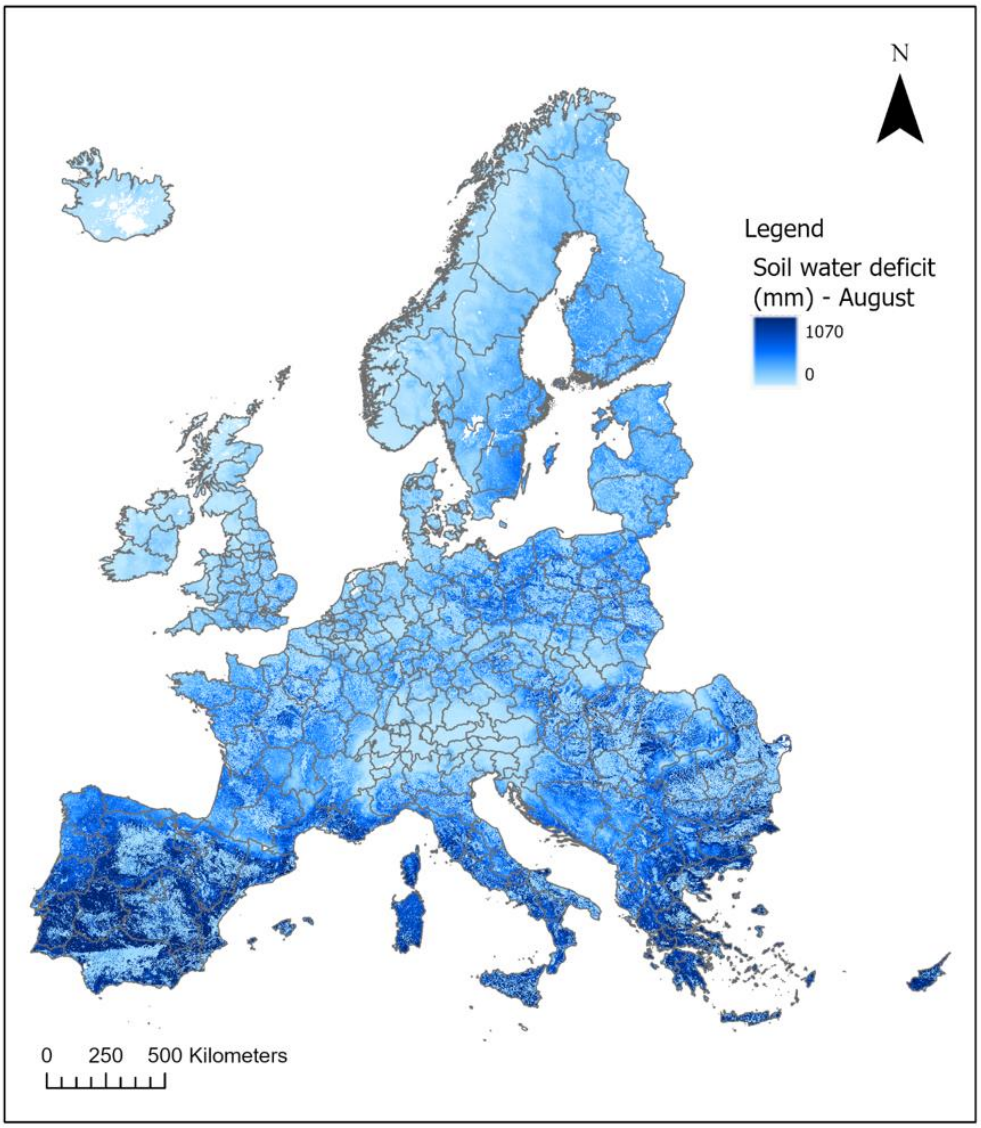


Figure A2.18: Soil water deficit map (month: August) for Europe as calculated by PESERA using long term climate input data.

A2.3.4. Soil improving measures

Four soil improvement measures were parameterized for PESERA: cover crops, mulching, compaction reduction, and minimum tillage. Two additional measure combinations were parameterized, combining compaction reduction and minimum tillage with either cover crops or mulching (assuming that cover crops and mulching cannot be combined). The combination measures assumed that no additive effects would occur for each parameter, taking instead the most intensive effect of each individual measure on each parameter. The description of each measure, and (in general terms) its implementation in PESERA, is described in Table A2.11.

Table A2.11: description of soil improving measures

Parameter	**Cover crops**	**Mulching**	**Compaction reduction**	**Minimum tillage**	**Cover crops +CR&MT**	**Mulching +CR&MT**
General description	Annual crops: cover crop in fallow period Permanent crops: cover crop in interrows	0.2 kg/m^2 mulching added each year	Decrease in use of heavy machinery	Tillage depth reduced by 40% (except root crops); 40% stubble cover left	Cover crops, compaction reduction and minimum tillage	Mulching, compaction reduction and minimum tillage
Soil surface						
Erodibility	=	=	=	-1 class	-1 class	-1 class
Cover	80% of bare soil	80% of bare soil	=	40% of bare soil	80% of bare soil	80% of bare soil
Roughness	+5 mm	+ 10 mm	=	+5 mm	+5 mm	+10 mm
Hydrological properties						
Water storage capacity*	+25%	+ 30%	+10%	=	+25%	+30%
Soil evaporation	=	-40%	=	=	=	-40%
Root depth	=	=	+10%	=	+10%	+10%
Vegetation						
Water use (wue)	Permanent crops: +0.1	=	=	=	Permanent crops: +0.1	=
Active period	Annual crops: cover crop in fallow period (0.6 kg/m^2)	=	=	=	Annual crops: cover crop in fallow period (0.6 kg/m^2)	=
Soil Organic Matter						
SOM breakdown rate	=	=	=	Decreased in tillage month	Decreased in tillage month	Decreased in tillage month

SOM added to soil	0.06 kg/m^2 at tillage	0.01 kg/m^2 each month (except tillage and harvest)	=	=	0.06 kg/m^2 at tillage	0.01 kg/m^2 each month (except tillage and harvest)

* Applied to 30 cm topsoil layer

The measures were tested on a synthetic dataset, representative of climatic and crop conditions in the Oceanic climate regions of Europe. The results of the application of each measure, and the combination of measures, were compared with those for no measure. The resulting level of impact was compared with results taken from a survey of meta-analyses published in indexed journals, including the impacts of cover crops, mulching and minimum tillage on soil erosion, Soil Organic Matter and biomass growth / crop yield (Table A2.12). No meta-analyses were found for compaction reduction nor for the combined measures, and only a limited number of studies focused on soil erosion.

Table A2.12: impact of measures according to literature (references are in Table A2.13).

Crop	**Impact on yield**	**Impact on SOC**	**Impact on erosion**
Minimum Tillage			
All crops	-7% (-13% to -3%) [4, 16]	11% (0% to 30%) [1, 12, 15]	-
Cereals	-5% (-13% to -3%) [9, 16, 18]	5% (0% to 20%) [2]	-
Root crops	-11% (-20% to -2%) [16, 18]	-	-
Vegetables	-20% (-30% to -10%) [16]	-	-
Permanent crops	-10% (-26% to 16%) [14]	42% (22% to 82%) [14]	-
Cover crops			
All crops	11% (4% to 22%) [6]	12% (7% to 19%) [6, 7, 8]	-86% (-91% to -81%) [6, 8]
Cereals	13% (4% to 22%) [13]	19% (16% to 22%) [7]	-
Root crops	-	-	-
Vegetables	-	13% (5% to 20%) [7]	-
Permanent crops	11% (-18% to 57%) [14]	16% (5% to 35%) [14]	-
Mulching			
All crops	16% (10% to 20%) (median of 5, 10, 17)	21% (14% to 29%) (median of 3, 11)	-
Cereals	16% (10% to 22%) [5, 17]	12% (11% to 14%) [11]	-
Root crops	16% (12% to 20%) [10]	-	-

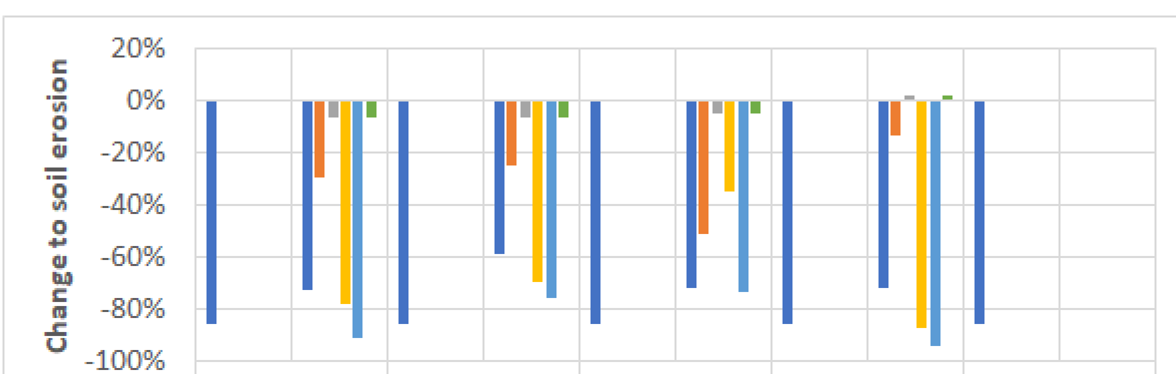
Vegetables	-	-	-
Permanent crops	-	30% (16% to 44%) [3]	-

Table A2.13: references mentioned in Table A2.12.

1	Aguilera et al. 2013	Aguilera E., Lassaletta L., Gattinger A., Gimeno B.S. 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems and Environment 168: 25–36. http://dx.doi.org/10.1016/j.agee.2013.02.003
2	Angers and Eriksen-Hamel 2008	Angers D.A., Eriksen-Hamel N.S. 2008. Full-Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-Analysis. Soil Sci. Soc. Am. J. 72: 1370-1374. doi:10.2136/sssaj2007.0342
3	Chen et al. 2020	Chen G., Liu S., Xiang Y., Tang X., Liu H., Yao B., Luo X. 2020. Impact of living mulch on soil C:N:P stoichiometry in orchards across China: A meta-analysis examining climatic, edaphic, and biotic dependency. Pedosphere 30(2): 181–189. doi:10.1016/S1002-0160(20)60003-0
4	Cooper et al. 2016	Cooper J., Baranski M., Stewart G. et al. 2016. Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron. Sustain. Dev. 36: 22. https://doi.org/10.1007/s13593-016-0354-1
5	Gao et al. 2019	Gao H., Yan C., Liu Q., Li Z., Yang X., Qi R. 2019. Exploring optimal soil mulching to enhance yield and water use efficiency in maize cropping in China: A meta-analysis. Agricultural Water Management 225: 105741. https://doi.org/10.1016/j.agwat.2019.105741
6	Jian et al. 2020b	Jian J., Du X., Reiter M.S., Stewart R.D. 2020b. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biology and Biochemistry 143: 107735. https://doi.org/10.1016/j.soilbio.2020.107735.
7	Jian et al. 2020a	Jian J., Lester B.J., Du X., Reiter M.S., Stewart R.D. 2020a. A calculator to quantify cover crop effects on soil health and productivity. Soil & Tillage Research 199: 104575. https://doi.org/10.1016/j.still.2020.104575
8	Keizer and Hessel 2019	Keizer J.J., Hessel R. 2019. Quantifying the effectiveness of stakeholder-selected measures against individual and combined soil threats. Catena 182: 104148. DOI: 10.1016/j.catena.2019.104148.
9	Knapp & van der Heiden 2018	Knapp S., van der Heijden M.G. 2018. A global meta-analysis of yield stability in organic and conservation agriculture. Nature communications 9(1): 1-9.
10	Li et al. 2018	Li Q., Li H., Zhang L., Zhang S., Chen Y. 2018. Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis. Field Crops Research 221: 50–60. https://doi.org/10.1016/j.fcr.2018.02.017
11	Lu 2014	Lu F. 2014 How can straw incorporation management impact on soil carbon storage? A meta-analysis. Mitig Adapt Strateg Glob Change. DOI 10.1007/s11027-014-9564-5
12	Luo et al. 2010	Luo Z., Wang E., Sun O.J. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems and Environment 139: 224–231. doi:10.1016/j.agee.2010.08.006
13	Marcillo and	Marcillo G.S., Miguez F.E. 2017. Corn yield response to winter cover crops: An updated

	Miguez 2017	meta-analysis. Journal of Soil and Water Conservation 72: 3. doi: 10.2489/jswc.72.3.226
14	Morugán-Coronado et al. 2020	Morugán-Coronado A., Linares C., Gómez-López M.D., Faz Á., Zornoza R. 2020. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agricultural Systems 178: 102736.
15	Nunes et al. 2020	Nunes M.R., Karlen D.L., Veum K.S., Moorman T.B., Cambardella C.A. 2020. Biological soil health indicators respond to tillage intensity: A US meta-analysis. Geoderma 369: 114335. https://doi.org/10.1016/j.geoderma.2020.114335
16	Pittelkow et al. 2015	Pittelkow C.M., Linquist B.A., Lundy M.E., Liang X., van Groenigen K.J., Lee J., van Gestel N., Six J., Venterea R.T., van Kessel C. 2015. When does no-till yield more? A global meta-analysis. Field Crops Research 183: 156–168. http://dx.doi.org/10.1016/j.fcr.2015.07.020
17	Qin et al. 2015	Qin W., Hu C., Oenema O. 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. Scientific Reports 5: 16210. DOI: 10.1038/srep16210
18	van den Putte et al, 2010	Van den Putte A., Govers G., Diels J., Gillijns K., Demuzere M. 2010. Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. European Journal of Agronomy 33(3): 231–241. doi:10.1016/j.eja.2010.05.008

The results are shown in Figure A2.19; as can be seen, the simulated measures broadly followed what was expected from the literature in terms of erosion reduction, increase in SOM and biomass, with some exceptions. First, results for permanent crops tend not to be very good: no changes are simulated to erosion, because the baseline values are zero when using the test data; changes to SOM are very limited; and changes to biomass are only correctly simulated for cover crops. This indicates that the model is better adapted to simulate annual crops than permanent crops. Second, PESERA does not simulate the expected decrease in biomass growth for minimum tillage, possibly because this is driven by changes to nutrient availability which are not simulated by the model.



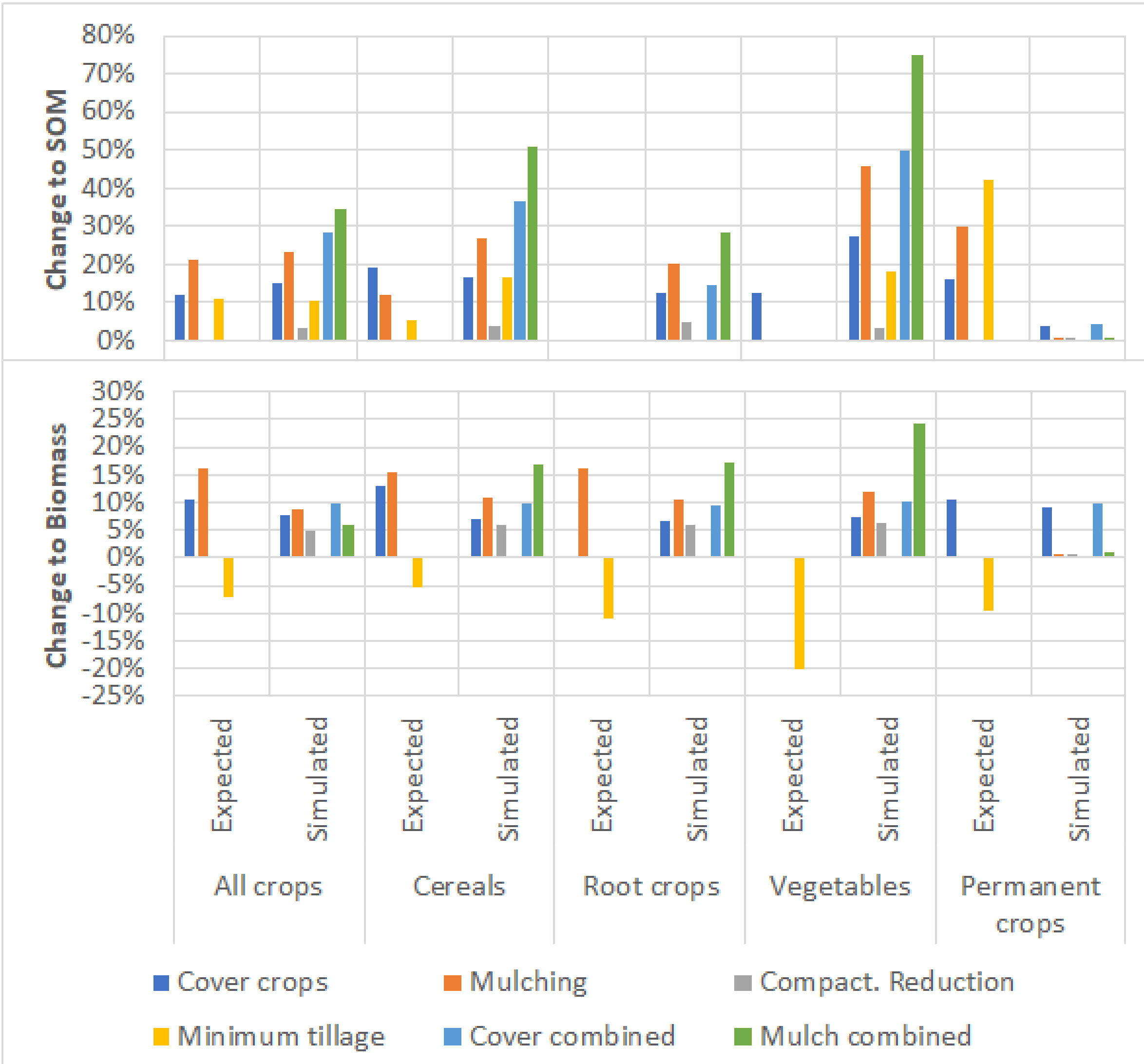


Figure A2.19: impact of different measures (expected and simulated with PESERA) on different types of crops, for (top) erosion, (mid) Soil Organic Matter and (low) biomass.

In any case, these results already show the small effects of compaction reduction when compared with other measures. For soil erosion control, mulching seems to have a limited effect when compared with cover crops and minimum tillage; this results from the wetter soil conditions, which increase yield (and, indirectly, SOM) by limiting water stress, but also create the right conditions for more frequent runoff generation, counteracting beneficial soil protection effects. For SOM, mulching has a slightly higher benefit than cover crops or minimum tillage;

while for biomass yield, minimum tillage has no effects, while cover crops and especially mulching lead to increases.

As for the combination measures, both tend to lead to higher increases of SOM and biomass yield when compared with the individual components. For soil erosion, the combined cover crop approach led to larger reductions than the individual components. However, the combined mulch approach had a very limited impact on soil erosion, despite the erosion decrease expected when applying the individual components; the wetter soil conditions and runoff increase counteract the soil protection effects of the measures. In short, results suggest that the combined cover crop approach appears to have a better balance between SOM increase, yield increase and erosion control, while the combined mulching approach has larger increases of SOM and yield at the expense of the effects on erosion control.

A2.3.5. SOC results for Europe 2020-2050

Fig A2.20 shows the simulated development of SOC over time in the RttB scenario in Europe from 2020, 2030, 2040 and 2050. The general spatial pattern shows that most SOC is in forest areas and in northern Europe. SOC seems to increase in these areas over time, while a decrease is visible in arable areas in e.g. north-central Iberia and the UK. This can be seen in more detail in the summaries per climate region in Figure A2.21. Permanent crops and forests show an increase in SOC until 2050, probably due to improved growth conditions throughout Europe. SOC in annual crops show either stability (fodder maize, root crops) or some decrease (remaining crops), which is consistent for the different climate regions of Europe. Since biomass from annual crops is higher, here the warmer climate promotes faster SOC decomposition.

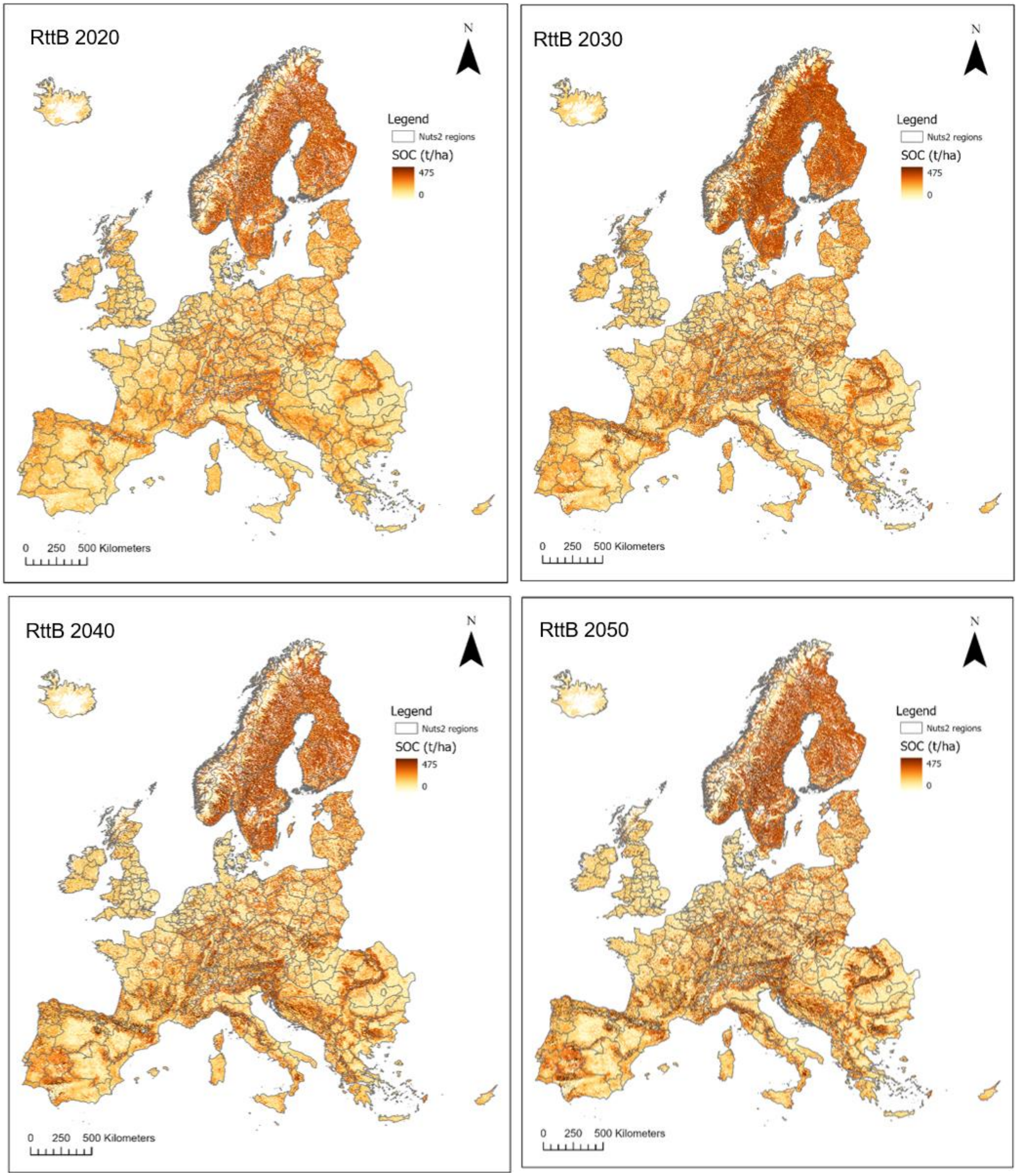


Figure A2.20: Evolution of SOC content (t/ha) over time for scenario Race to the Bottom in 2020, 2030, 2040, 2050.

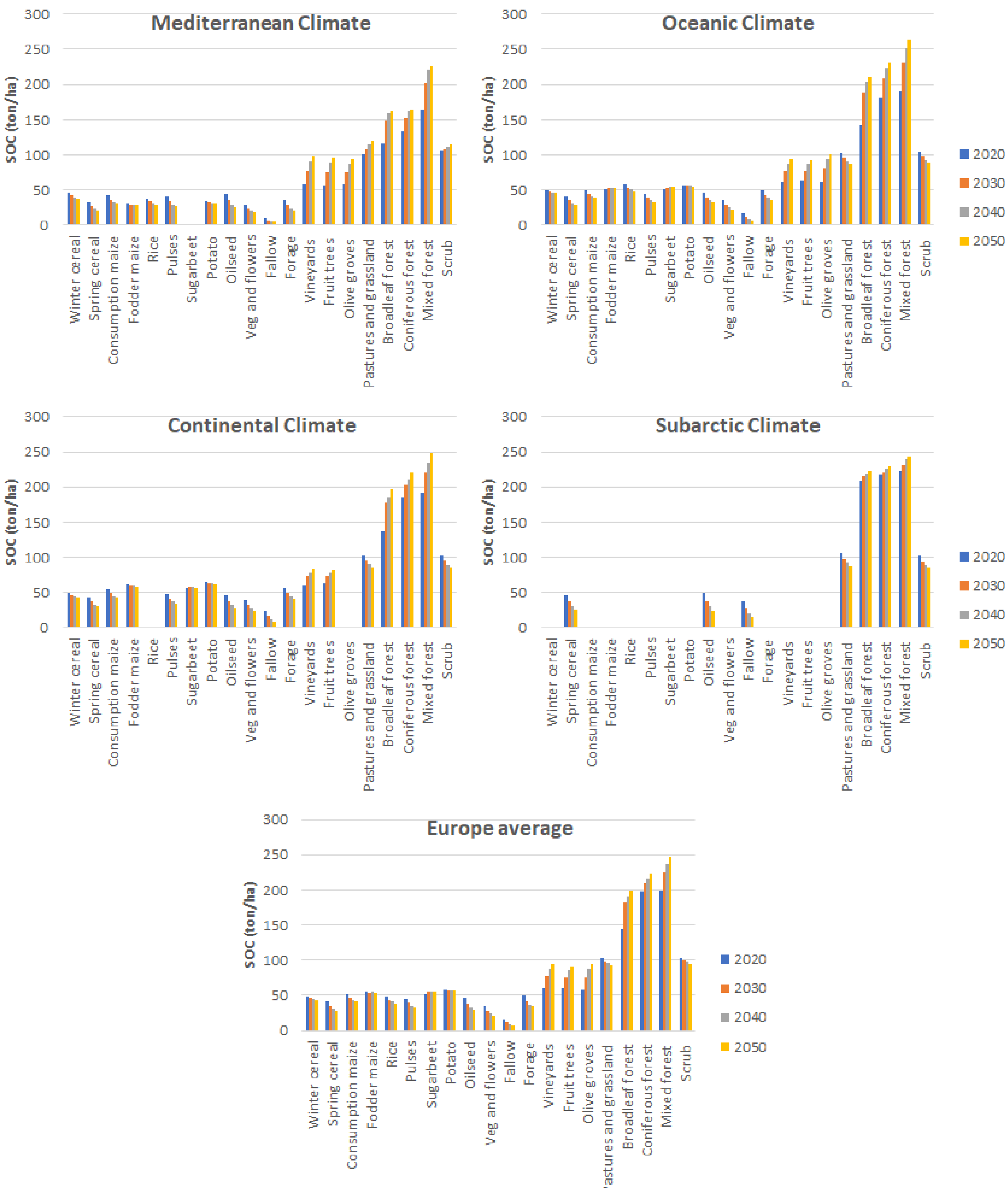


Figure A2.21: Evolution of SOC content (t/ha) over time for scenario Race to the Bottom in 2020, 2030, 2040, 2050, summarized by crop and land use in the climate regions of Europe.

Annex 3: Dyna-QUEFTS DATA AND CALIBRATION

A3.1. Overview of model information

Name of the model

Dyna-QUEFTS

Scope and aim of the model

Simulation of expected crop yield levels under native soil fertility conditions as well as fertilization practices. The model has also been used to specify fertilization requirements for a given target yield.

Main concepts and modelling paradigm

QUEFTS considers empirical nutrient concentration variations and ratios between the main plant nutrients N, P and K. The model assumes yields are nutrient-limited.

Scale the model has been applied to and can be applied to

To calibrate the model, large datasets of crop yields and nutrient uptake under variable native soil nutrient conditions and fertilizations are needed. Typically QUEFTS is calibrated for a crop and a range of soil fertility conditions. As such it has been applied in many mostly tropical locations, but has more recently also been applied in temperate zones. Calibrations exist for a variety of crops.

Is the model spatially explicit?

Yes. The model operates on a grid.

Spatial resolution of the model and flexibility of this resolution

The model has so far been applied to grid cells with a resolution varying between 300 m. and 500 m.

Does the model include temporal dynamics?

Yes. Temporal dynamics are crucial in the model as results for a time t+1 build on results from time t.

Temporal resolution of the model and flexibility of this resolution

The model works on a yearly resolution.

External drivers included

Main drivers of change when running the model for future years are changes in climate inputs such as temperature and crop choice inputs, as well as changing soil organic matter levels.

Management options included

DYNA-QUEFTS allows the user to set values for N, P and K inputs (fertilisation).

Indicators calculated

DYNA-QUEFTS calculates the nutrient limited yield as well as P and K content in the soil.

Input data required and desired

DYNA-QUEFTS requires maps as input.

- Climate data: annual temperature maps of average temperature over the crop growing period.
- Soil data: pH, K, P, and soil organic matter maps.
- Numerical data: nutrient input (NPK) through fertilization, atmospheric deposition and N-fixation.

Parameters required and desired

Required: minimum and maximum nutrient concentrations in plants, nutrient harvest index, nutrient recovery fraction, crop dry matter content, potential crop yield;

Desired: minimum nutrient uptake below which crop does not produce yield

Data required for calibration and validation

Soil nutrient data, fertilization data, yield data

Calibration and validation process

Comparison of modelled yields with observed yields. Adjusting model parameters to improve fit.

Outputs

- Crop yield (raster file)
- Soil nutrient concentration (P, K) (raster files)

Run-time of the model

For Europe in the order of minutes.

Availability of model

Yes, DYNA-QUEFTS is available without additional costs as part of the project.

Availability of model developer

Yes, DYNA-QUEFTS is developed and being maintained by RIKS and WUR.

Availability of source code

Yes, to the consortium partners.

Programming language

C++

Possibility to re-use worldwide

Yes.

Ability to adapt to meet requirements

High.

Common uses in combination with other models

Integration with Metronamica and PESERA in LANDSIM-P (WorldBank LAUREL project).

Potential and limitation for integration with other models

None.

Additional remarks

None.

A3.2. Input data description and sources

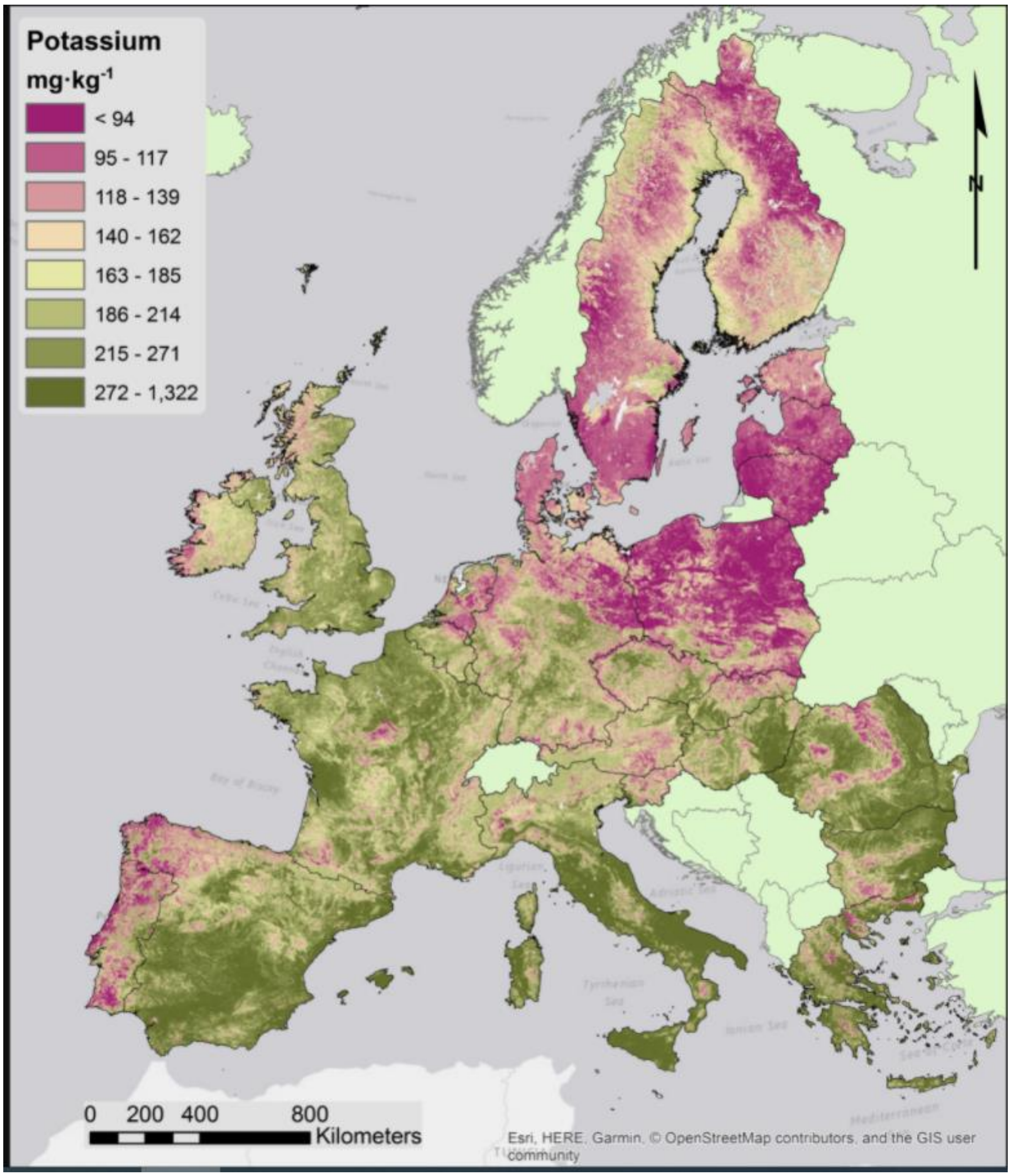
A3.2.1. Soil nutrient maps

Data source:

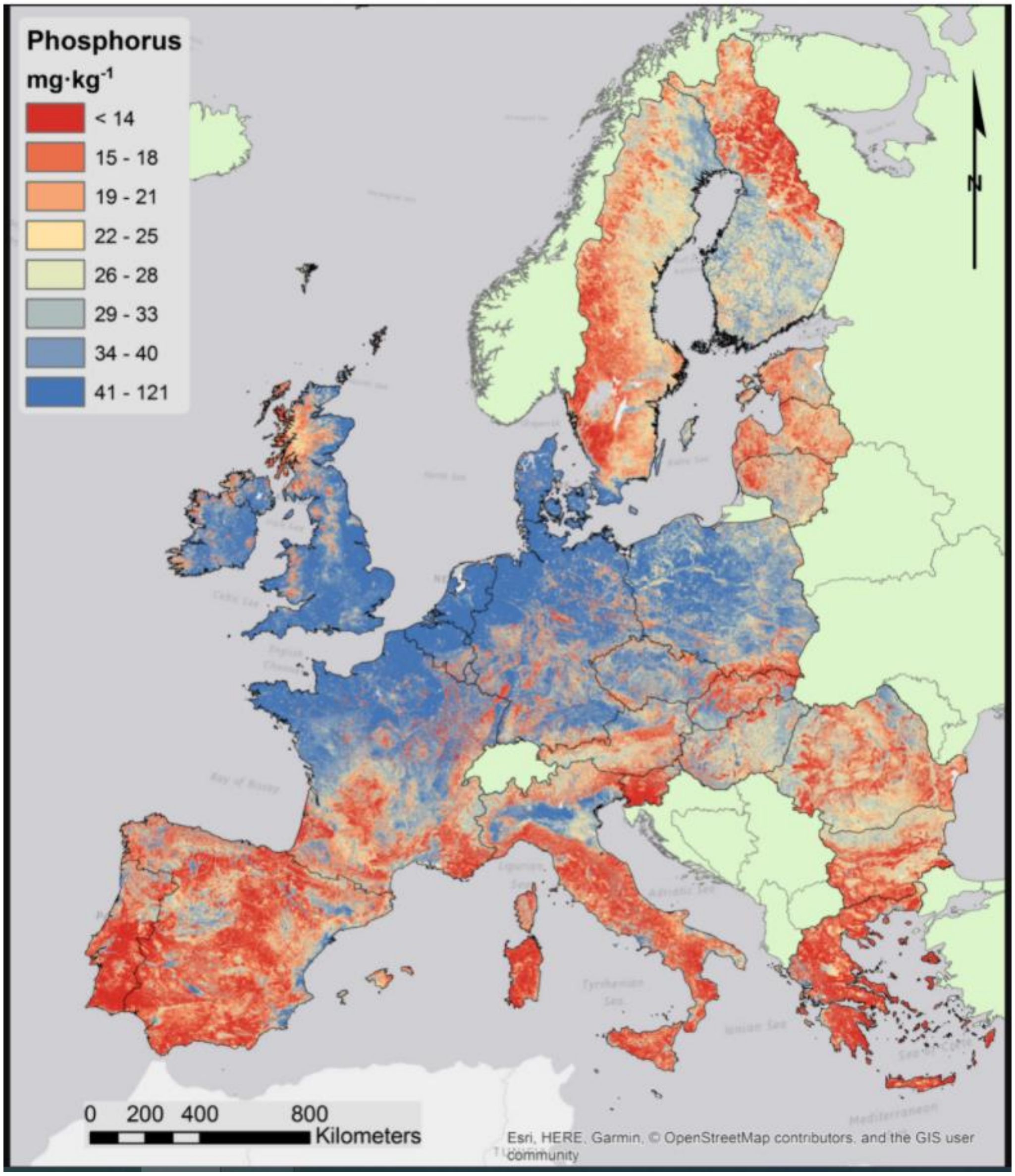
Maps of Soil Chemical properties at European scale based on LUCAS 2009/2012 topsoil data as described in Ballabio et al. (2019) were used and obtained from: https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data

LUCAS data are based on 0-20 cm soil depth sampling, which conveniently coincides with QUEFTS input requirements. Maps are represented at a 500 x 500 m grid resolution. Missing data for Balkan countries, Iceland, Norway and Switzerland was filled in by using average values for arable land in neighbouring countries.

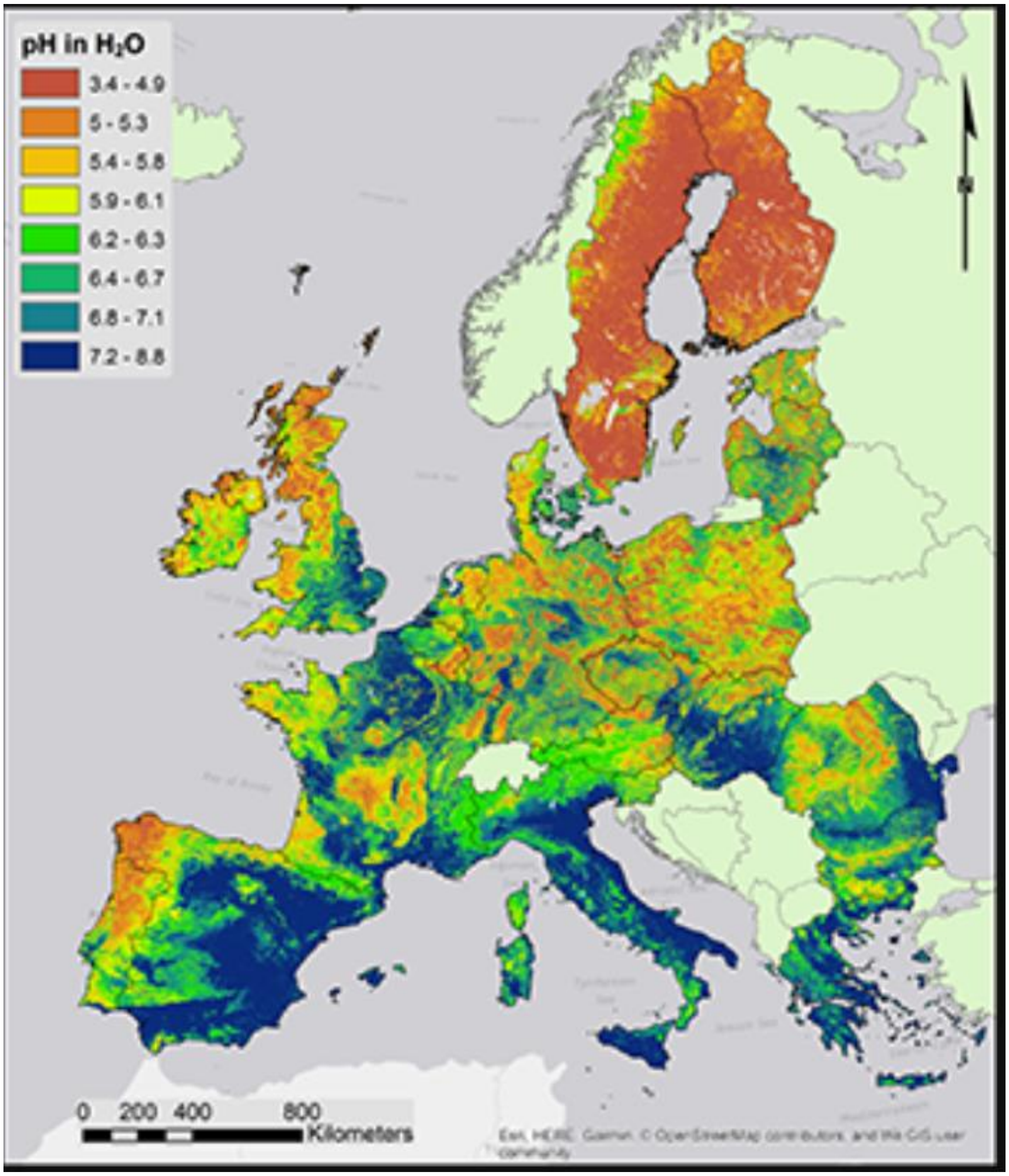
- Exchangeable K (in mmol/kg). Exchangeable K in LUCAS is measured based on USDA NRCS (2004) (Orgiazzi et al., 2018) Extractable K content in mg/kg was converted to mmol/kg, using molar mass of 39.0983.



- P_olsen (available P in soil to plants) (in mg/kg). In LUCAS soluble P is measured based on ISO 11263 (1994) (Orgiazzi et al., 2018).



● pH_H20


pH in H_2O
3.4 - 4.9
5 - 5.3
5.4 - 5.8
5.9 - 6.1
6.2 - 6.3
6.4 - 6.7
6.8 - 7.1
7.2 - 8.8
0 200 400 800
Kilometers

A3.2.2. Soil organic carbon

Data source: PESERA simulation (humus output). QUEFTS requires SOC concentration in g/kg. PESERA provides humus output in kg/m2. A conversion factor of 2.0764 is applied, resulting from a bulk density of 1.4 ton/m3, a soil depth of 20 cm and a SOC to SOM conversion factor of 1.78.

A3.2.3. Temperature

Data source: Crop calendars were defined as described under the PESERA input data. QUEFTS requires average temperature over crop-specific growing seasons. Average monthly temperature map data prepared for the PESERA model was averaged over the growing season for each crop.

A3.2.4. Nutrient input

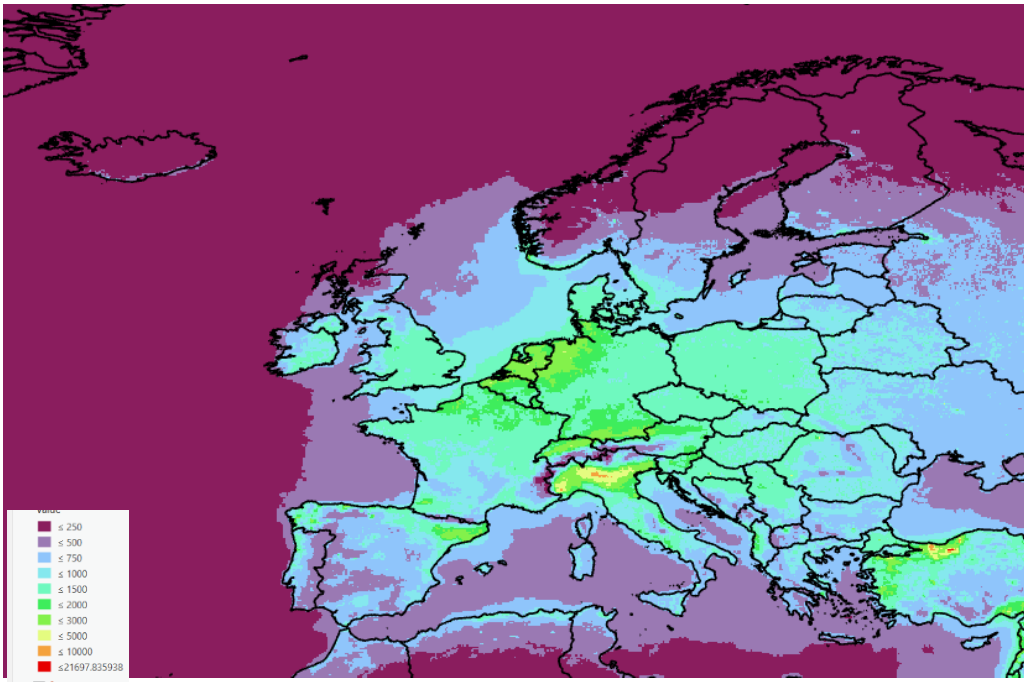
Atmospheric deposition

Data source:

N deposition in different forms was taken from EMEP (https://emep.int/mscw/mscw_moddata.html) for 2018, and averaged for arable cropland in each of the countries considered (range 2-21 kg ha-1 year-1).

K deposition was estimated at 2 kg ha-1 year-1 based on Hellsten et al (2007).

Nutrient deposition is taken to be available for the part of the year crops are grown (i.e., a fraction corresponding to the time of the year crops are grown is considered).



Combined wet and dry atmospheric N deposition over Europe (units: mg N/m2)

Fertilization

Information on N, P, and K nutrient input is required for Dyna-QUEFTS. This information can either be provided by crop as tabular input, or varied geographically (e.g. across countries) in the form of maps. The development of N, P, K nutrient application rates (as tables for country level applications and as maps for the Europe-wide model application) was part of the model calibration process.

Key sources for this assessment were:

- Fertilizer application taken from MITERRA publication (year 2000 data)
- Animal manure application calculated following MITERRA procedures for N, P and K
- Free living N fixation added (2 kg ha-1 year-1)
- N fixation pulses assumed to be generated by N fixation of plant by inverse reasoning

A3.3 Parameterization, tuning and performance assessment

A3.3.1. Review QUEFTS applications for different crops and crop parameterizations

A literature review was performed to compile studies applying QUEFTS in continental, temperate and subtropical climate zones for crops grown in Europe. QUEFTS parameterisations obtained in these studies were compiled in a table. The maximum accumulation (an, ap, ak) and maximum dilution (dn, dp, dk) indicators (kg nutrient/kg yield) were visually plotted as box plots to identify outliers. On the upper end, values within the interquartile range were selected as maximum parameters. On the lower end, extreme values (>1.5 times the interquartile range) were excluded. The hence identified upper and lower values were considered as the range within which to parameterize QUEFTS. Few studies reported minimum required nutrient uptake to produce yield (rn, rp and rk indicators) - hence these were set to 0. As very extensive (non-fertilized and low input) crop cultivation is rare in Europe, this was deemed unlikely to influence the calibration. The tables below present an overview of the parameterizations in the literature for different crop types. Bold figures represent the extreme values across the studies. Blue (maximum) and red (minimum) cells indicate the range of values considered for QUEFTS parameterisation. Minimum range values were only considered where maximum values did not provide sufficient space for calibration. Tables A3.1-A3.8 show the final sets used for Dyna-QUEFTS. Nutrient recovery fractions were taken from the applications and used as a calibration factor if necessary.

The following crop types could be parameterized based on existing QUEFTS calibrations:

- Cereals: 6 studies were found that applied QUEFTS to wheat (5) and barley (1) respectively.
- Maize: 6 studies applied QUEFTS to maize.
- Rice: 4 studies parameterized QUEFTS for rice.
- Pulses: 3 studies applied QUEFTS to soybean (2) and peanut (1) respectively. Groundnut is hardly grown in Europe, so parameterizations for soybean were used.
- Sugarbeet: 1 study applied QUEFTS to sugarbeet.

- Potatoes: 3 studies were found that applied QUEFTS to potatoes.
- Oilseeds: 3 studies parameterised QUEFTS for rapeseed (2) and sunflower (1) respectively.

Table A3.1: QUEFTS parameterisations for cereals in literature.

	Cereals						
Crop	wheat	wheat	wheat	wheat	wheat	barley	barley
Source	Sattari etal 2014	Chuan etal 2013	Liu etal 2006	Maiti et al, 2006	Pathak et al (2003)	Janssen, 2011	
Case study	UK - Broadbalk	China	China	India	India	Netherlands - eastern Flevopolder	
Year	1987, 1992, 1997, 2000	2000-2011	1985-1995	2001-2003	1970-1998	1975-2002	
an (kg/kg)	30	28.8	25	**35**	27	30	**16**
ap (kg/kg)	135	98.9	**171**	129	162	100	**93**
ak (kg/kg)	25	23	24	**17**	20	**30**	26
dn (kg/kg)	70	62.6	**56**	**100**	60	**90**	72
dp (kg/kg)	500	487.4	367	**738**	390	**300**	506
dk (kg/kg)	70	**112.9**	67	**56**	59	90	99
ratio dn/an	2.33	2.17	2.24	2.86	2.22	3.00	4.50
ratio dp/ap	3.70	4.93	2.15	5.72	2.41	3.00	5.44
ratio dk/ak	2.80	4.91	2.79	3.29	2.95	3.00	3.81
N recovery fraction (%)			45 (7.6-82.3)	40		90	
P recovery fraction (%)			22 (9.8-43.4)	20		30	
K recovery fraction (%)			47 (4.0-91.7)	50		90	
rn (kg/ha)		28.8	0				
rp (kg/ha)		98.9	0				
rk (kg/ha)		23	0				
yield (ton/ha)	5.5		0.35-8.73	1.5-5.5		4.21	
potential yield (ton/ha)			6-12 (Mao, 2003)	7			
Harvest index (kg/kg)		0.44 (0.18-0.69)	0.18-0.65				

Table A3.2: QUEFTS parameterisations for maize in literature.

	Maize							
Source	Jiang etal 2017	Liu etal 2006	Xu etal 2013	Xu etal 2013	Xu etal 2013	Zhang et al (2012)	Sattari etal 2014	Setiyono etal, 2010
Case study	China - northeast	China	China	China	China	China (north)	USA, Cairo-Nebraska	USA, Cairo-Nebraska
Year	2006-2011	1985-1995					2002-2004	2002-2004
an (kg/kg)	34.1	21	32	36	31	**44**	32	40
ap (kg/kg)	151.8	126	11	135	108	209	155	**225**
ak (kg/kg)	40.2	20	31	30	32	**68**	39	29
dn (kg/kg)	**93.3**	64	83	89	70	83	75	83
dp (kg/kg)	410.9	384	525	558	435	484	595	**726**
dk (kg/kg)	**184.4**	90	123	132	110	184	170	125
ratio dn/an	2.74	3.05	2.59	2.47	2.26	1.89	2.34	2.08
ratio dp/ap	2.71	3.05	47.73	4.13	4.03	2.32	3.84	3.23
ratio dk/ak	4.59	4.50	3.97	4.40	3.44	2.71	4.36	4.31
N recovery fraction		0.50 (0.13-0.87)					0.6	
P recovery fraction		0.24 (0.05-0.52)					0.2	
K recovery fraction		0.44 (0.05-0.80)					0.5	
yield (ton/ha)	8.86 (2.54-14.2)	0.55-10.98	8.53 (1.65-17.86)				16	12.01 (0.32-19.01)
potential yield (ton/ha)		7-13 (Zhang, 2001)						
Harvest index (kg/kg)	0.46 (0.20-0.69)	0.1-0.68	0.47 (0.19-0.77)					0.5 (0.17-0.62)

Table A3.3: QUEFTS parameterisations for rice in literature.

	Rice			
Source	Xu etal 2015	Sattari etal 2014 - ba	Das et al 2009	Buresh et al (2010)
Case study	China	China - Hebei	India	S+ SE + E Asia
Year	2000-2013	1978-1991		
an (kg/kg)	34	**48**	**31**	43
ap (kg/kg)	**140**	**206**	192	202
ak (kg/kg)	**28**	**36**	33	36
dn (kg/kg)	90	**96**	**87**	94
dp (kg/kg)	**576**	589	**678**	595
dk (kg/kg)	94	**102**	**81**	95
ratio dn/an	2.65	2.00	2.81	2.19
ratio dp/ap	4.11	2.86	3.53	2.95
ratio dk/ak	3.36	2.83	2.45	2.64
N recovery fraction		0.6		
P recovery fraction		0.2		
K recovery fraction				
yield (ton/ha)		9		
potential yield (ton/ha)	16			
Harvest index (kg/kg)	0.4			

Table A3.4: QUEFTS parameterisations for pulses in literature.

	pulses		
Crop	soybean	soybean	peanut
Source	Jiang etal 2019	Yang etal 2019	Xie et al 2020
Case study	North-east China	China (major soybear	China
Year	2011-2013	2001-2015	1993-2018
an (kg/kg)	**10.5**	13.5	**17**
ap (kg/kg)	**65.6**	60.4	**136**
ak (kg/kg)	30.4	**27.8**	**31**
dn (kg/kg)	**20.6**	21.4	**36**
dp (kg/kg)	289.6	**234.6**	**365**
dk (kg/kg)	162.7	**79.9**	154
ratio dn/an	1.96	1.59	2.12
ratio dp/ap	4.41	3.88	2.68
ratio dk/ak	5.35	2.87	4.97
yield (ton/ha)	2.73 (0.8-4.48)	2.47 (0.53-6.51)	3.92 (0.5-8.6)
Harvest index (kg/kg)	0.42 (0.14-0.60)	0.46 (0.26-0.66)	

Table A3.5: QUEFTS parameterisations for sugarbeet in literature.

	sugarbeet	
Source	Janssen, 2011?	
Case study	Flevoland	
Year	1994-1999	
an (kg/kg)	**45**	34
ap (kg/kg)	**300**	196
ak (kg/kg)	**30**	20
dn (kg/kg)	135	**144**
dp (kg/kg)	900	**1865**
dk (kg/kg)	90	**180**
ratio dn/an	3.00	4.24
ratio dp/ap	3.00	9.52
ratio dk/ak	3.00	9.00
dry matter yield (ton/ha)	11.25	

Table A3.6: QUEFTS parameterisations for potatoes in literature

	potato		
Source	Xu etal 2019	Janssen, 2011	Kumar et al 2018
Case study	China	Netherlands	Indo-Gangetic plain
Year	1992-2017	1975-2002	
an (kg/kg)	**133**	38	133
ap (kg/kg)	652	136	**917**
ak (kg/kg)	119	17	**139**
dn (kg/kg)	463	105	**594**
dp (kg/kg)	**3030**	814	2606
dk (kg/kg)	**790**	74	350
ratio dn/an	3.48	2.76	4.46
ratio dp/ap	4.65	5.99	2.84
ratio dk/ak	6.64	4.35	2.52
yield (ton/ha)	25.1 (0.4-75.9)	67.2	
Harvest index (kg/kg)	0.74 (0.40-0.95)		

Table A3.7: QUEFTS parameterizations for oilseeds in literature.

	oilseeds			
Crop	rapeseed	rapeseed	rapeseed	oil sunflower
Source	Ren etal 2016	idem	Zou et al 2011	Shu-tian etal 2018
Case study	China		China	China
Year	2005-2010		2000-2007	2014-2016
an (kg/kg)	**5.5**	13.1		**14.7**
ap (kg/kg)	**21.7**	**68.9**		30.6
ak (kg/kg)	**1.9**	**8.9**	9.1	5.3
dn (kg/kg)	**36.5**	**31.6**		34.8
dp (kg/kg)	**267.4**	200.3		**182.5**
dk (kg/kg)	**70**	31.1	70	**16.3**
ratio dn/an	6.64	2.41		2.37
ratio dp/ap	12.32	2.91		5.96
ratio dk/ak	36.84	3.49		3.08
N recovery fraction	36 (0.1-102)			
P recovery fraction	20 (-18-69)			
K recovery fraction	43 (-36-162)			
rn (kg/ha)	0.8			
rp (kg/ha)	0.2			
rk (kg/ha)	0.2			
yield (ton/ha)	1.81 (0-4.73)		2.21 (0.96-4.73)	3.70 (1.20-5.52)
Harvest index (kg/kg)	0.29 (0.06-0.40)			0.29

Table A3.8: Final sets of QUEFTS maximum accumulation and dilution parameters used in setting up Dyna-QUEFTS.

Wheat	Set 1	Set 2	Set 3	Set 4
aN	16	16	30	30
aP	93	93	162	162
aK	17	17	26	26
dN	56	90	90	90
dP	300	506	506	506
dK	56	99	99	112.9
Foodmaize	**Set 1**	**Set 2**		
aN	40	44		
aP	225	225		
aK	68	68		
dN	93	93		
dP	726	726		
dK	184	184		
Rice	**Set 1**	**Set 2**		
aN	31	48		
aP	140	206		
aK	28	36		
dN	87	96		
dP	576	589		
dK	81	102		
Pulses	**Set 1**	**Set 2**		
aN	10.5	13.5		
aP	60.4	65.5		
aK	27.8	30.4		
dN	20.6	21.4		
dP	234.6	289.6		
dK	79.9	162.7		
Sugarbeet	**Set 1**	**Set 2**		
aN	45	45		
aP	300	300		
aK	30	30		
dN	144	144		
dP	1865	1865		
dK	180	180		
Potato	**Set 1**	**Set 2**		
aN	133	133		
aP	652	917		
aK	119	139		
dN	463	594		
dP	3030	3030		
dK	790	790		
Oilseed	**Set 1**	**Set 2**		
aN	13.1	13.1		
aP	68.9	68.9		
aK	8.9	8.9		
dN	31.6	36.5		
dP	267.4	267.4		
dK	31.1	70		

A3.3.2. Manure application

Data on manure quantities and management systems was obtained from Hou et al. (2017) for reference year 2010. This paper presents data distributing the total manure production per country over different manure management systems with different nutrient loss rates and nutrient application to grassland and arable land. Animal N excretion rates were taken from Velthof et al. (2015). Animal data from 2010 needed to be updated to 2018 stock number to calculate the manure application quantities for the base year 2018. AGMEMOD cattle and pig stock data for 2018 was used for this purpose, complemented with FAOSTAT 2017 data on sheep, goat and poultry numbers. Base rates of manure application to different crops, divided into three groups, were based on the Miterra procedure explained in Velthof et al. (2007). Nutrient recovery rates from manure application were collected, but in the end needed to be heightened to fertilizer nutrient recovery rates in QUEFTS yield calibrations. Manure application rates were adjusted as part of the QUEFTS calibration process. Two main levers were used for this:

1. Increasing the share of nutrients to arable crops by reducing the percentage of cattle manure applied to grassland and fodder crops
2. Shifting the crop membership of either of the three manure application groups (Default group 1: potatoes, sugar beet, other crops, other vegetables, barley, rape, soft wheat; group 2: durum wheat, rye, oats, other cereals, grain maize, sunflower; group 3: fruits, trees, olives, oil crops, citrus, grapes, other crops, receiving respectively the bulk, 75% of average, and 10% of average manure application rates - Velthof et al., 2007)

A3.3.3. Fertilizer application

Fertilizer application was considered in a very similar way as manure application. The application rates given by Velthof et al. (2007) were used as a basis. The key lever for nutrient applications was the distribution of fertilizer use over cropland and grassland. A balancing of nutrient allocation rates was made by considering fertilizer use and sales data from Eurostat.

Calibration procedure at country level:

1. Reallocate manure and fertilizer application over cropland and grassland, or between crops
2. Select appropriate QUEFTS crop parameter set
3. Refine nutrient recovery fractions

Calibration target was the AGMEMOD yield for 2020, which is based on a projection of observed national average yields over the period 2000-2018 and has the advantage that it is not affected by regionally climate-impacted yield reductions across Europe. Yet, AGMEMOD yields featured some gaps and extreme values, which were filled in with FAO 2019 yield statistics if these were clearly more in line with nutrient application levels. Calibrations were done for 19 countries for which data availability was most complete: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the United Kingdom. Quite good results were obtained for the yield simulations for the 9 selected crops (Figure A3.1).

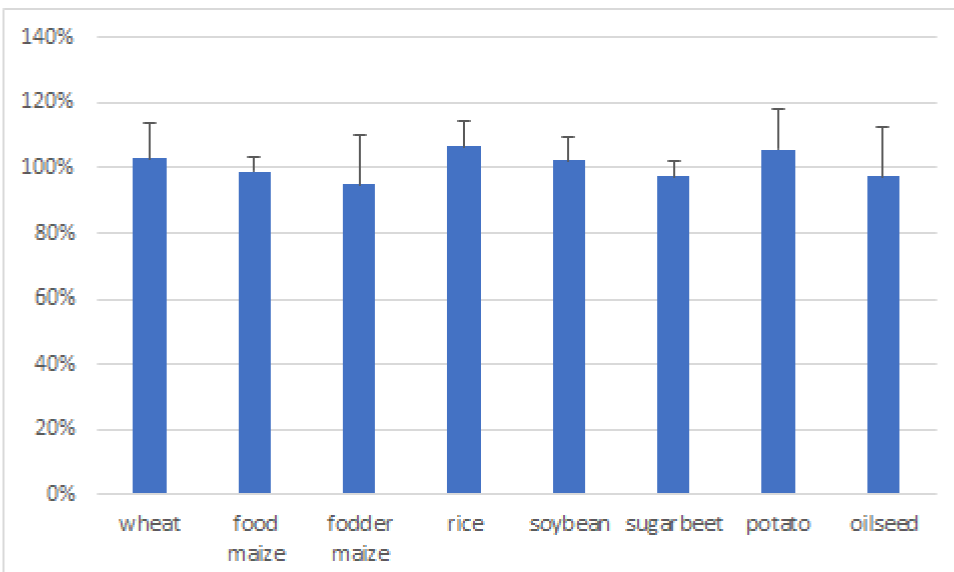


Figure A3.1. Relative difference and standard deviation between modelled and observed (agricultural statistics) yields.

The model calibrations for these 19 countries were used to construct a linear yield prediction model that could inform the NPK application rates in remaining model countries (Albania, Bosnia-Herzegovina, Croatia, Cyprus, Estonia, Germany, Iceland, Kosovo, Latvia, Liechtenstein, Lithuania, Luxemburg, Malta, Montenegro, North Macedonia, Norway, Slovenia, and Switzerland). Using these models, NPK application rates were predicted. Restrictions were put in place to avoid negative nutrient application rates and, as a minimum, consider the nutrient budget contributions of atmospheric deposition and free-living soil bacteria.

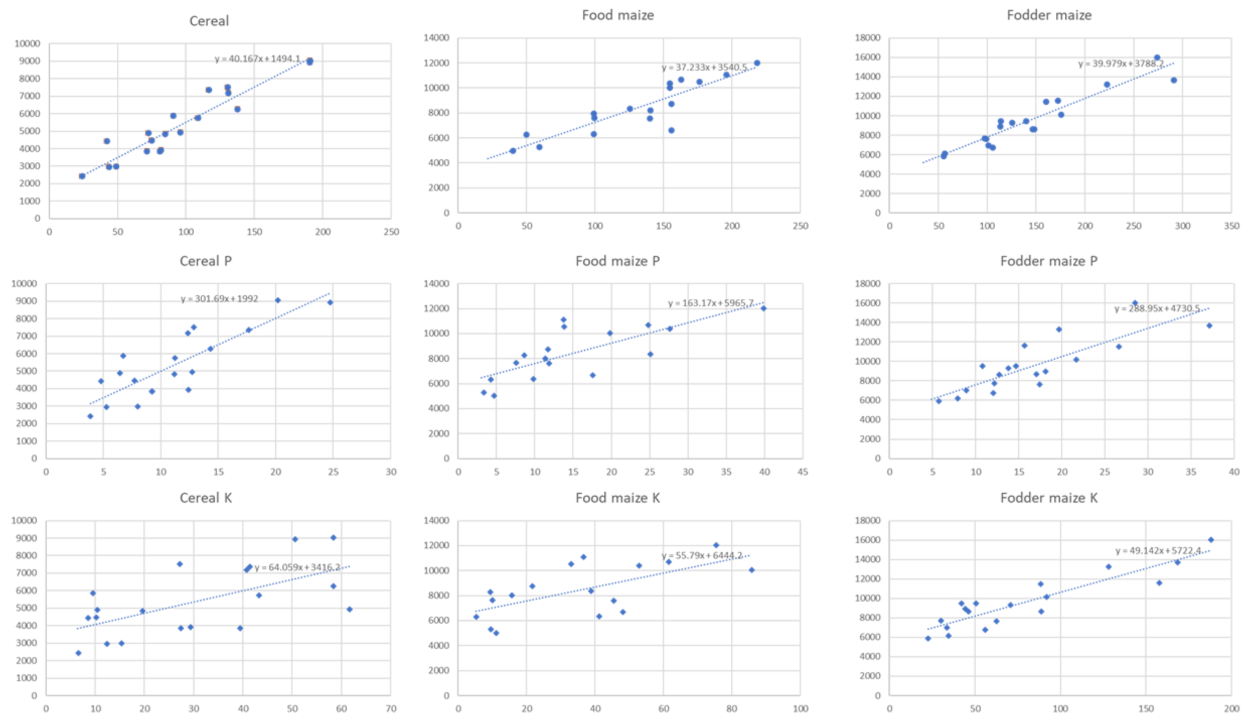


Figure A3.2. Example yield prediction models based on NPK application in 19 calibrated countries.

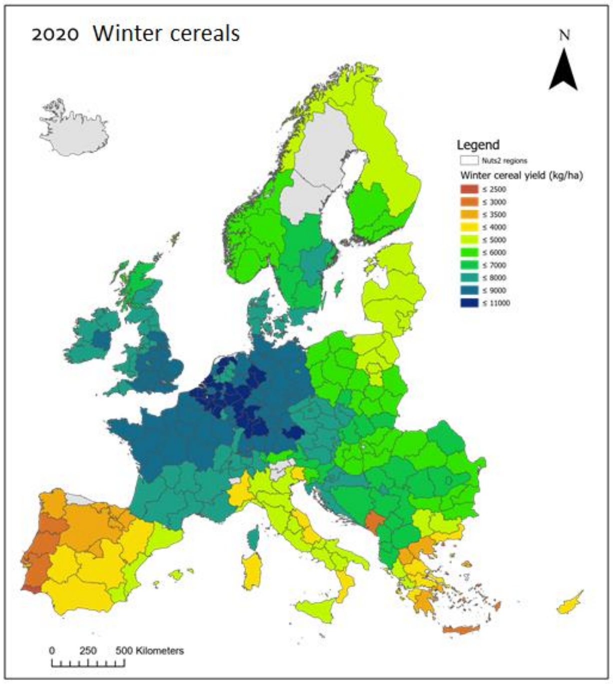
The next step in calibration for the 18 remaining countries was to set the QUEFTS model parameters to values that would support in reaching targeted model yield levels. For this, the settings for these parameters in the 19 calibrated countries were plotted against modelled yields. Stylized thresholds were derived from these plots for N recovery fractions and the QUEFTS maximum accumulation and dilution parameter sets. These classifications are given in the Table A3.9 below.

Table A3.9: QUEFTS parameterization for non-calibrated countries.

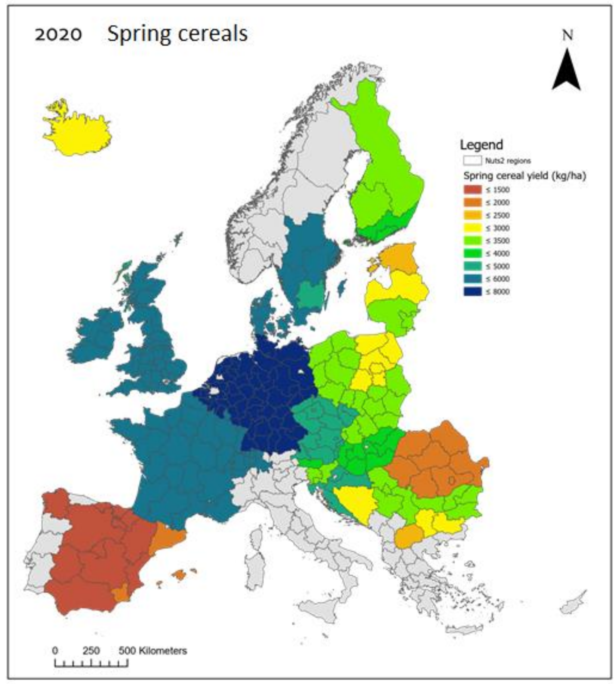
	Recovery fraction N			QUEFTS parameter set	
	Yield class	Value		Yield class	Set choice
Wheat	<3000	0.4		<3000	1
	>3000	0.55		3000-6000	3
				>6000	4
Maize	overall average	0.53		n.a.	1
Fodder maize	overall average	0.56		n.a.	1
Rice	<4000	0.4		Eastern Mediteranean	2
	5000-7000	0.5			
	>7000	0.55			
Pulses	linear model	0.91-0.98		<1500	1
				>1500	2
Sugarbeet	overall average	0.55		n.a.	1
Potato	overall average	0.5		<40000	1
				>4000	2
Oilseeds	<2000	0.4		<2500	1
	2000-3000	0.5		>2500	2
	>3000	0.6			

A3.3.4. Calibrated crop yield in initial year

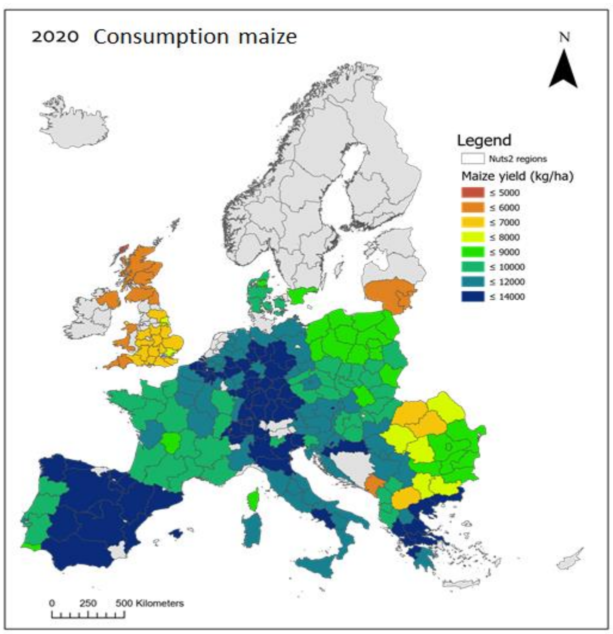
The SoilCare IAM was used to simulate crop yields for 9 crops (winter cereals, spring cereals, consumption maize, fodder maize, rice, pulses, sugarbeet, potatoes and oilseeds). Figure A3.3 shows the average yields per NUTS-2 region. Not all crops are grown across Europe, as can be seen from the grey spaces in the figures. Yield levels follow a gradient of intensification (fertilization levels), water availability and temperature constraints. Generally Northwest Europe boasts the highest yields, whereas Subarctic and Mediterranean environments present challenges to agricultural production, respectively in terms of cold and drought. Eastern European countries have less intensive fertilization practices, which leads to lower yields, although yields have increased most in this region in recent years. A counterintuitive pattern can be discerned for some crops, e.g. consumption maize, which is fully irrigated in Mediterranean countries, which hence feature the highest yields. To some extent, yield variability is also caused by crop groupings of crops that are quite diverse, e.g. pulses (various beans and peas) and oilseeds (rapeseed, sunflower).



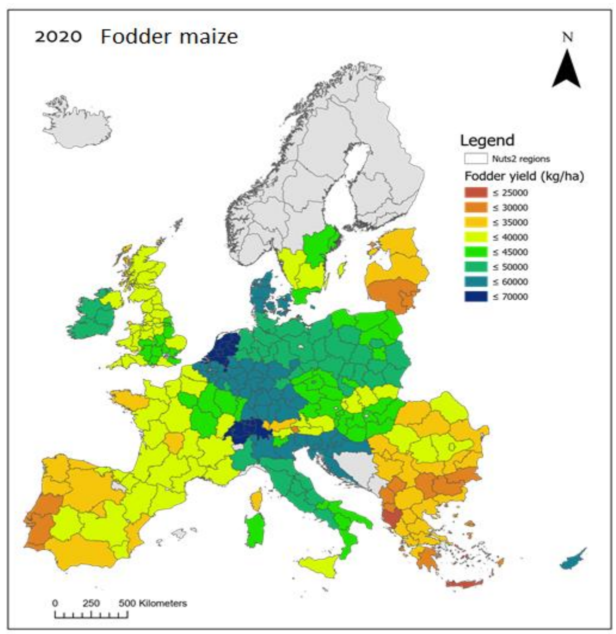
2020 Winter cereals
N
Legend
Nuts2 regions
Winter cereal yield (kg/ha)
≤ 2500
≤ 3000
≤ 3500
≤ 4000
≤ 5000
≤ 6000
≤ 7000
≤ 8000
≤ 9000
≤ 11000
0 250 500 Kilometers



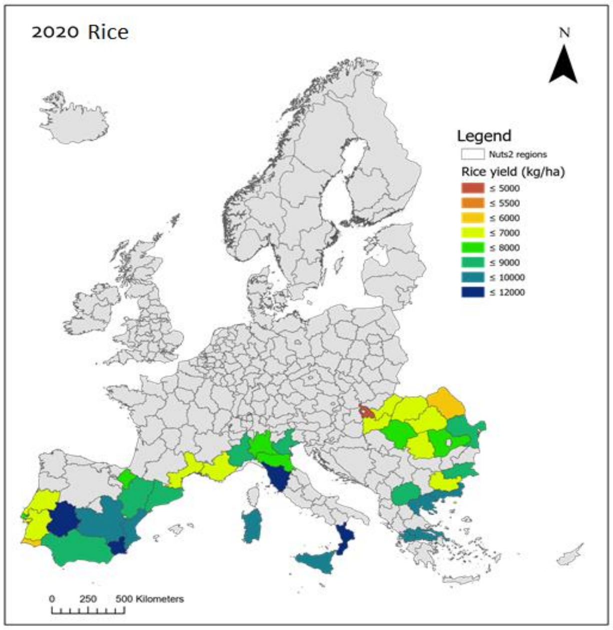
2020 Spring cereals
N
Legend
Nuts2 regions
Spring cereal yield (kg/ha)
≤ 1500
≤ 2000
≤ 2500
≤ 3000
≤ 3500
≤ 4000
≤ 5000
≤ 6000
≤ 8000
0 250 500 Kilometers

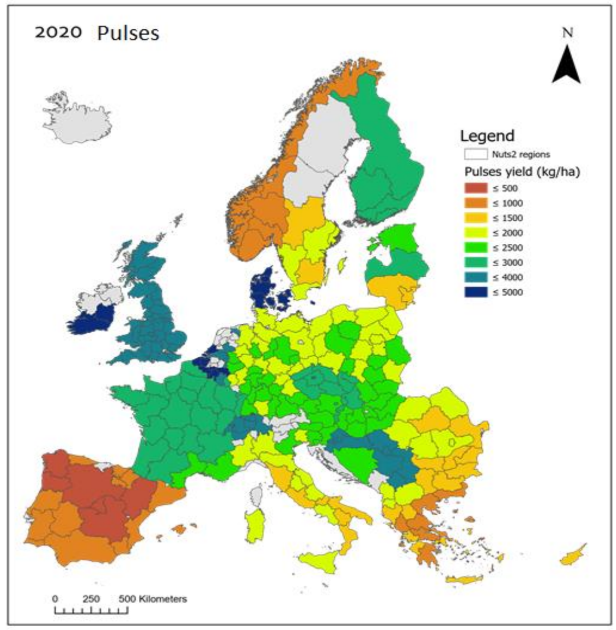


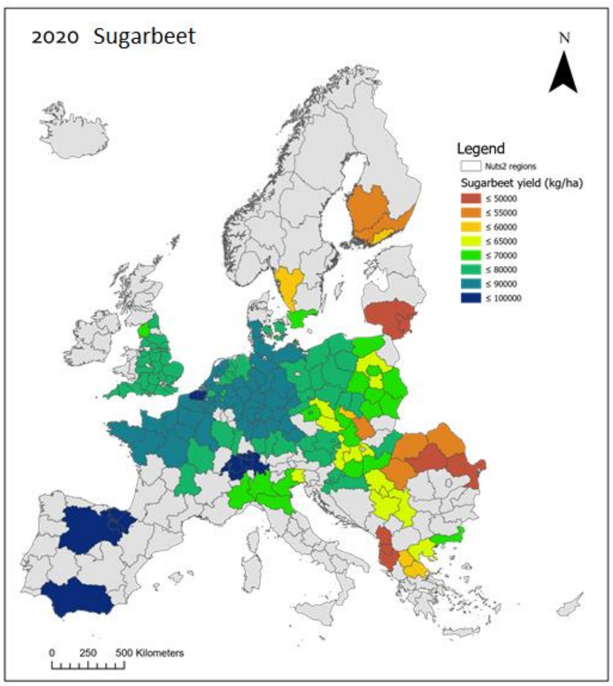
2020 Consumption maize
N
Legend
Nuts2 regions
Maize yield (kg/ha)
≤ 5000
≤ 6000
≤ 7000
≤ 8000
≤ 9000
≤ 10000
≤ 12000
≤ 14000
0 250 500 Kilometers

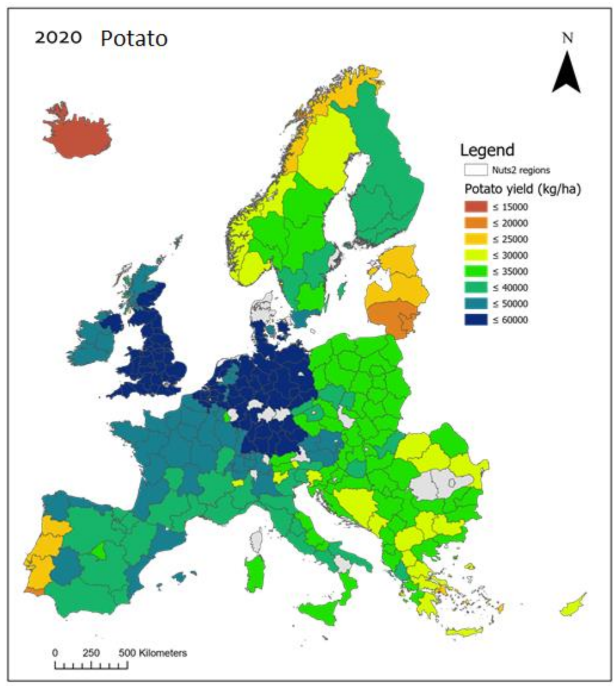


2020 Fodder maize
N
Legend
Nuts2 regions
Fodder yield (kg/ha)
≤ 25000
≤ 30000
≤ 35000
≤ 40000
≤ 45000
≤ 50000
≤ 60000
≤ 70000
0 250 500 Kilometers


2020 Rice
N
Legend
Nuts2 regions
Rice yield (kg/ha)
≤ 5000
≤ 5500
≤ 6000
≤ 7000
≤ 8000
≤ 9000
≤ 10000
≤ 12000
0 250 500 Kilometers


2020 Pulses
N
Legend
Nuts2 regions
Pulses yield (kg/ha)
≤ 500
≤ 1000
≤ 1500
≤ 2000
≤ 2500
≤ 3000
≤ 4000
≤ 5000
0 250 500 Kilometers


2020 Sugarbeet
N
Legend
Nuts2 regions
Sugarbeet yield (kg/ha)
≤ 50000
≤ 55000
≤ 60000
≤ 65000
≤ 70000
≤ 80000
≤ 90000
≤ 100000
0 250 500 Kilometers


2020 Potato
N
Legend
Nuts2 regions
Potato yield (kg/ha)
≤ 15000
≤ 20000
≤ 25000
≤ 30000
≤ 35000
≤ 40000
≤ 50000
≤ 60000
0 250 500 Kilometers

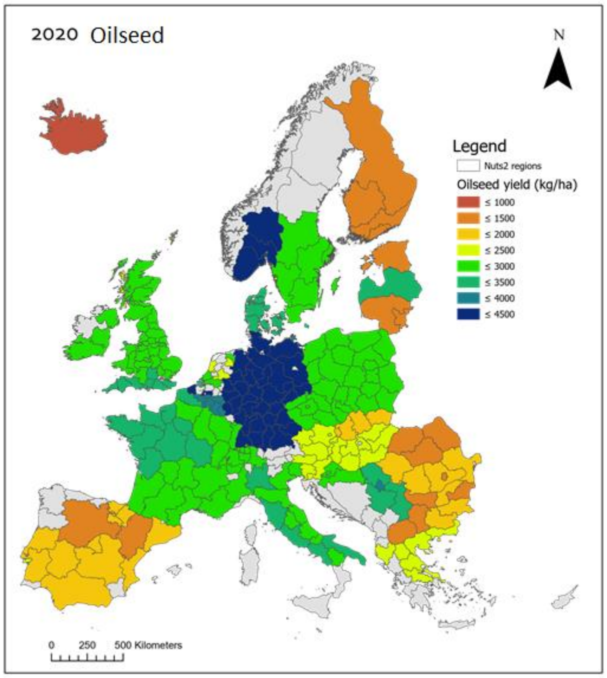


FIgure A3.3. Average crop yields per NUTS-2 regions.

Results were presented as NUTS2-level averages as visualizing the pixel-level results is less clear. See examples below for cereals and pulses.

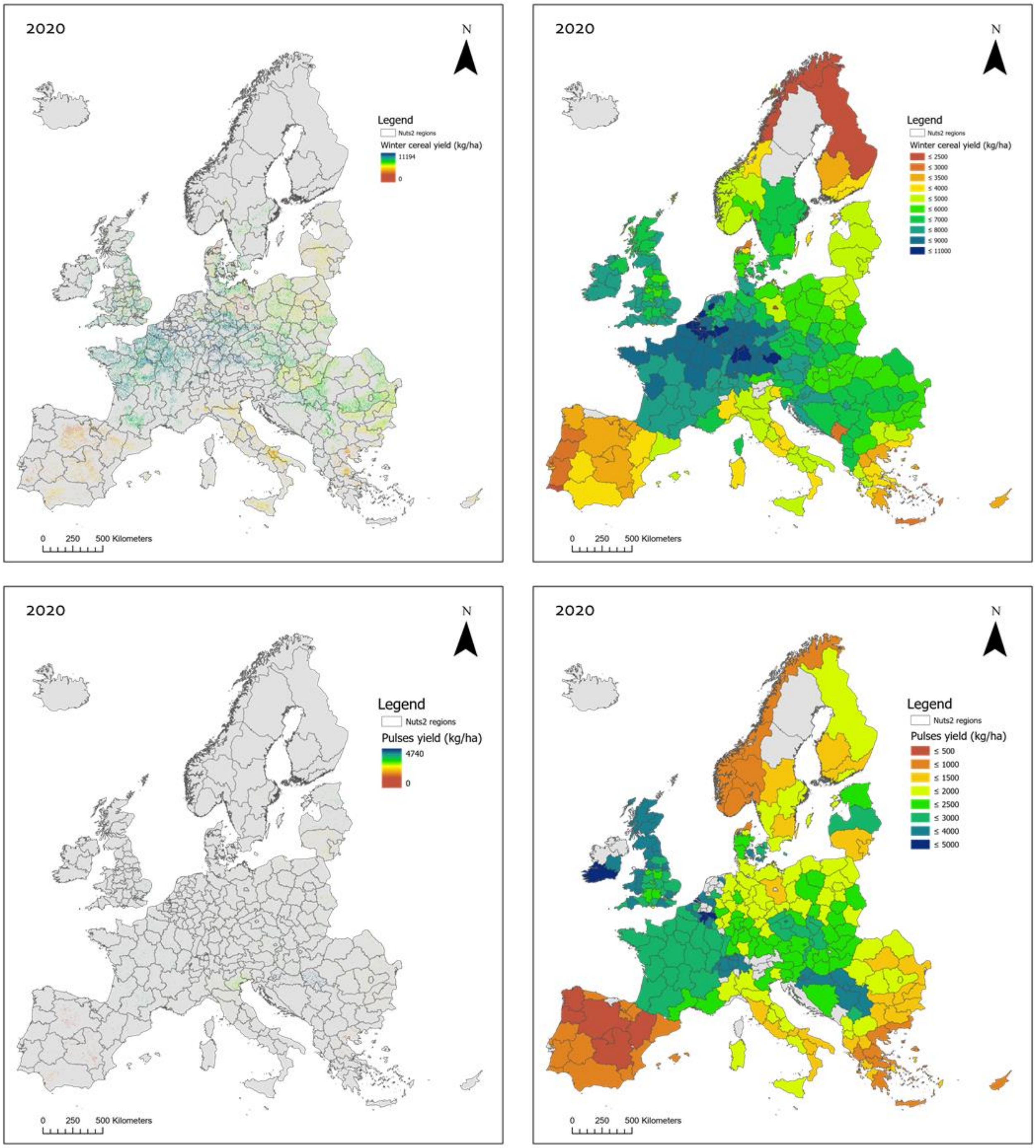


Figure A3.4. Visualization of the superiority of NUTS-2 level visualization, especially for crops with scattered sparse representation across Europe (e.g. pulses).

Annex 4: MITERRA INCLUSION OF MEASURES

This annex describes some of the implementation details for incorporating the measures in MITERRA.

A4.1. Cover crops

The current implementation of cover crops is derived from Eurostat data at NUTS-2 level from the agri-environmental indicator 'Soil Cover', which is based on information from the Farm System Survey (FSS) of 2016[1]. This indicator provides information on the soil cover and distinguishes the following classes: normal winter crop, cover crop, multi-annual plants, plant residues and bare soil. The current cover crop share has been derived from these data, see Figure A4.1. Based on this data the current (2016) area under cover crops is about 7.6 million ha in the EU-28. For the technical potential we assumed that cover crops can be applied on 80% of the area that is currently under bare soil or plant residues (Figure A4.1), which would increase the total area under cover crops to 33.7 million ha.

The carbon input from cover crops depends very much on the biomass yield of the cover crop, which is determined by the species, time of seeding, winter hardness and availability of water. No European wide information on cover crop yield is available. Jacobs et al. (2020) found an average carbon input of 0.3 ton C/ha/year for Germany, but this is the average for all arable land. Based on the areas that actually have cover crops (11% of the site years) the C input is about 3 ton C/ha/year, however, based on the map in that article, the average C input seems to be lower, around 1 ton C/ha. Poeplau and Don (2015) calculated an average C input of 1.87 ton C/ha/year for cover crops, based on backwards calculation of global LTE studies with RothC. Based on these data, an average C input of 1.5 ton/ha/year has been used for all cover crops throughout Europe. This is a simplification as there is likely to be a climate effect as well, but data is currently lacking for a more precise estimate of the C inputs from cover crops.

Current cover crop share | Potential cover crop share

[1] https://ec.europa.eu/eurostat/databrowser/view/ef_mp_soil/default/table?lang=en

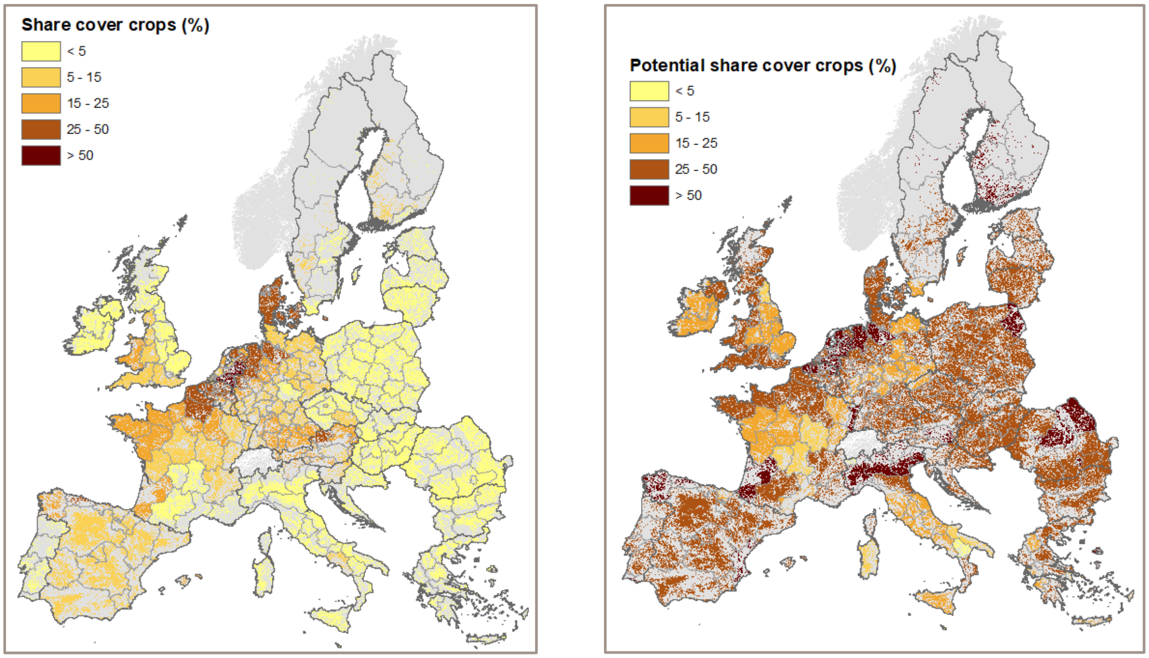


Figure A4.1. Current cover crop share on arable land (left), based on FSS 2016, and the potential cover crop share (right) as used for the simulation

Besides an impact on carbon, the cover crops can also have an impact on nitrogen flows, as they prevent leaching during the winter season. When the cover crop is incorporated, the nitrogen becomes available for the following crop. In this way the amount of fertilizer application can be reduced. Based on a literature survey and meta-analysis in the H2020 Fairway project, an average reduction of N leaching by 45% was found. In addition we assume that N surface runoff is reduced by 25% following Velthof et al. (2009). Furthermore we assume a reduction in N fertilizer based on the amount of N in the cover crops. Data on C/N ratios in cover crops are scarce, and show quite high variation, with low C/N ratios for leguminous cover crop species and high ratios for others. We have assumed an average C/N ratio of 35, which means that 42 kg N/ha is taken up by the cover crop. This amount is added to the crop residues in the calculation, and part of this nitrogen will be mineralised and become available for the following crop. The model calculates the amount of mineral N fertilizer that can be saved.

A4.2. Reduced tillage

The current implementation of reduced tillage practices is derived from the Eurostat agri-environmental indicator Tillage, which is based on data from the 2016 farm system survey[2]. The total area under reduced tillage practices was in 2016 about 20.5 million ha and in addition 3.8 million ha was under zero tillage practices. As can be seen from Figure A4.2 the area under reduced tillage is in some regions already more than 50% of the arable land. For the technical potential we assumed that reduced tillage will be applied on 80% of the area that is currently under conventional tillage, which results in a total area of 75 million ha under reduced tillage.

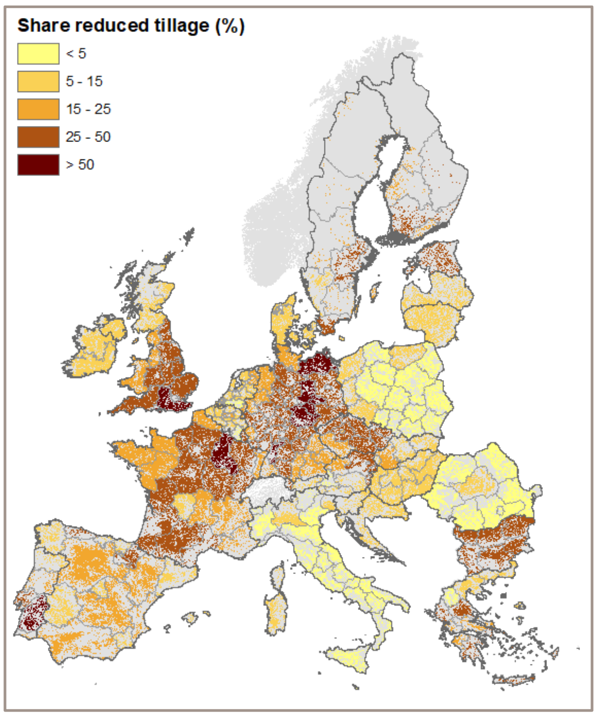


Figure A4.2. Current share of reduced tillage on arable land based on FSS 2016 data

For modelling the effect of reduced tillage on soil carbon, the RothC model is not directly appropriate, as it does not have a ploughing factor. Based on the IPCC guidelines, it is possible to make an estimate of the impact on soil carbon, based on the so-called stock change factor for management (F_{mg}). This factor is climate dependent, see table A4.1. For dry zones the effect of reduced tillage is negative, while for moist zones an increase is predicted of 4% over the 20 year equilibrium period. For no till increases are predicted for all climate zones. However, for many of

[2] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ef_mp_prac&lang=en

the studies that were used to derive this, factors are only based on the topsoil, whereas more recent studies that looked also at the subsoil show that the net C sequestration over the entire soil profile is often around zero (Haddaway et al., 2017). These F_{mg} stock change factors have been annualised and are applied to the SOC stocks that are under reduced or zero tillage.

Table A4.1. Tillage factors (F_{mg}) from IPCC 2019 guidelines (IPCC, 2019)

	Full tillage	Reduced tillage	No-till
Cool temperate dry	1	0.98	1.03
Cool temperate moist	1	1.04	1.09
Warm temperate dry	1	0.99	1.04
Warm temperate moist	1	1.04	1.10

A4.3. Mulching

For mulching the data are based on previous simulations with MITERRA-Europe for the Europruning EU-project. For that project the sustainable harvest of prunings for bioenergy purposes was determined. The mulching of the pruning residues was only considered for perennial woody crops, which comprise in MITERRA-Europe the following crops: olives, vineyards, citrus trees, apple and pear trees and other fruits trees. As there is no statistical data on the current use of pruning residues, we assumed that in the baseline all pruning material is removed or burned, whereas in the scenario with mulching we assume that 80% of the prunings are used for mulching. In the model this will result in an additional input of carbon to the soil and a reduction of soil erosion. No impacts on fertilization and N emissions has been simulated for this measure. For soil erosion the cover factor will be reduced by 12%, which is the same as the reduction for plant residues that is used for the RUSLE equation by Panagos et al. (2015).

Annex 5: Stakeholder selection criteria - European level

	Criteria	Definition and further criteria	Justification - what information will this allow us to gain
1. **Level**	EU level	• Those working on EU policy level, or representing aggregate interests at the EU level	• Policy expertise at EU level – the theory and impact of high level policy
2. **Organisation type**	European Institutions	• Those working on soil and agricultural policy development/analysis/implementation • For the other policy areas, those working at the intersection of the policy area in question and agriculture • European Commission/JRC • Not the Parliament or Council	• Theoretical and practical expertise of the links between the policies and SICs • Interlinkages between policies • Successes and gaps • Future drivers and uncertainties • Aims, performance indicators • Adoption potential • Information and tool gaps/needs
	NGOs	• EU level • Environmental charities involved in soil/agricultural policy and the other policy areas in question • Policy technical experts (those involved in policy research, development and implementation) (not communications)	• Theoretical perspective and practical examples of policy mechanisms • Potentially a more critical perspective than policymakers • Successes and gaps • Future drivers and uncertainties • Aims, performance indicators Information and tool gaps/needs
	Farmer Associations	• EU level • Associations representing farmers • Policy technical experts (those involved in policy research, development and implementation) (not communications) • Those impacted by the policy who can tell us about likely effects of implementation	• How different policies might be implemented and therefore would affect behaviour (practical perspective) • Adoption potential • Future drivers and uncertainties • Aims, performance indicators • Information and tool gaps/needs
	Key academics	• Any academics that are intimately involved with research into the impact of policy on agricultural practices and cropping systems • Those that have already worked on similar EU projects e.g. SoCo	• Theoretical expertise about links between policies and practice • Knowledge of primary research • Future drivers and uncertainties • Adoption potential • Aims, performance indicators

3. **Policy area**			• Information and tool gaps/needs
	Industry	• Large organisations working at global or European scale or organisations representing the stakes of a particular group (e.g. an organisation for SMEs) • Those involved in strategic planning / strategy development • Those involved in following policy updates and implementing them in their organisation • Those most likely to be impacted by the policy who can tell us about likely effects of implementation	• Adoption potential • Future drivers and uncertainties • Aims, performance indicators • Information and tool gaps/needs
	8 identified policy areas that are most relevant for influencing adoption of SICS[3]	• To cover all agricultural and soil policies that impact on agricultural practices and cropping systems that farmers use or adopt • At the intersection of these policies and agriculture e.g. those working on biodiversity within agriculture. • Number of experts to be confirmed, but will not need more multiple experts for all the policy areas, because data will be triangulated with data from the policy and literature review.	• In-depth analysis of the whole range of policy areas relevant to adoption of SICs • In-depth primary data on interactions between policies

[3] The CAP Regulations, Fertiliser Regulation, Birds and Habitats Directives, the Sewage Sludge Directive, the Sustainable Use of Pesticides Directive the Water Framework Directive, Nitrates Directive, Flood Directive, Groundwater Directive, Drinking Water Directive, and the Directive on Environmental Quality Standards.

Annex 6: Interview script European level interviews

Introduction

What the project is about

Ø *WP7 Policies (and other factors) that impact what agricultural practices farmers adopt (especially SICS)*

Ø *WP6 Future scenarios for rural Europe affecting adoption of soil-improving agricultural practices and development of an Integrated Assessment Model (IAM) to evaluate the impact of policies under various future scenarios on a set of productivity and sustainability indicators*

Aims of the interviews

Ø *Deeper insight from experts in the field of policy aims and practices that impact which practices farmers adopt (especially those affecting soil), and other factors that condition the impact these policies have such as future climate and socio-economic developments*

Structure of the interviews

Ø *Semi-structured*

Ø *3 parts: 1) your background and expertise, 2) policies and practices, 3) future scenarios*

Ø *Focusing on their area of expertise (but touching on others as appropriate if they crop up)*

Consent

1. **Do you have any questions regarding our research or the interview?**
2. **Are you happy for the interview to be recorded?**
    - For researcher's personal information only – so that we can concentrate on the interview

Background questions

3. **Can you tell us a little but about the main areas that you work on in your current role?**
4. **What is the nature of that work?**
    - e.g. economic analysis, research, implementation

Current policies and other factors

5. **In your opinion what are the main factors that influence farmers' agricultural practices?**
    - Policies
    - Wider factors e.g. global markets, supply chains, cost of land, personal beliefs; geographical location
6. **Which policy areas in general you think have the biggest impact on farmers' agricultural practices?**
    - e.g. CAP, Water (Nitrates, Floods), Nature protection/biodiversity, Climate, Food Safety, IT/Tech
    - Programs e.g. LIFE, AIPs (CAP), research e.g. Horizon 2020
7. **And can you tell us about the ways in which the policies you work on affect farmers' agricultural practices?**
    - Do they place mandatory requirements on farmers?
    - Do they provide any economic incentives?
    - Do they change attitudes?
8. **Do you think that the policies are having the above impacts in practice?**
    - Can you think of any examples?
    - Are they being properly enforced?
    - What evaluations of the policies have been carried out and what were the main results?
    - Is there variation across regions/MS?

9. **Do you think that there are any other policies that affect how the policies that you work on impact on farmers' agricultural practices?**
    - Are their synergies between policies?
    - Are there any conflicting requirements or incentives placed on farmers?
10. **Which other wider contextual factors do you think also affect the implementation of these policies and their impact on practices?**
    - E.g. farmers' beliefs; institutions (e.g. finance, property rights); geographical location
    - Any practical examples?
    - Variation across regions/MS?

Future developments

Ø *Having talked about current drivers of farmers' agricultural practices, we would now like to think about future of rural Europe, how future developments will impact on the uptake of soil-improving practices, the effectiveness of current policies in that context as well as the need for new policies*

11. **What do you see as the key drivers of change in rural Europe over the next 50 years?**

    What are the impacts of these drivers?
    - on the adoption potential of SICS,
    - on the effectiveness of current policies, instruments and practices and the need for future policies, instruments and practices related to soil-improving agricultural practices, and
    - sustainable agriculture in general
12. **What are the main uncertainties over the next 50 years that could affect Europe's ability to have a sustainable and profitable agricultural sector?**
    - How do these impact on the uptake of SICS and the sustainability and profitability of the agricultural sector in Europe?
13. **Do you think that we need to change existing policies/ instruments with the future in mind?**
    - If so which policies and which instruments?
    - Do we need completely new policies?

- What other factors would need to change to ensure better implementation of the policies in question?

14. What type of information and tools do you currently use to support your work? And in your organisation/division/sector?

- What are those tools used for?
- Are there specific types of information or tools you feel could facilitate or enhance your work?

Conclusion

15. Are there any other issues that you would like to raise?

16. Are there any other people you feel we should talk about this topic?

Ø *Are you happy to be contacted for follow up questions or to clarify anything?*

Ø *We will send you a copy of the research*

Annex 7: Identification of relevant actions for SICS adoption

The following pages provide an overview of the format workshop participants were presented with for the activity ‘Identification of relevant actions for SICS adoption’ and the actions they defined. As discussed in Sections 4.1 and 4.4, input is provided per scenario. On the next pages results are provided per scenario. Scenario names are provided on top of each page.

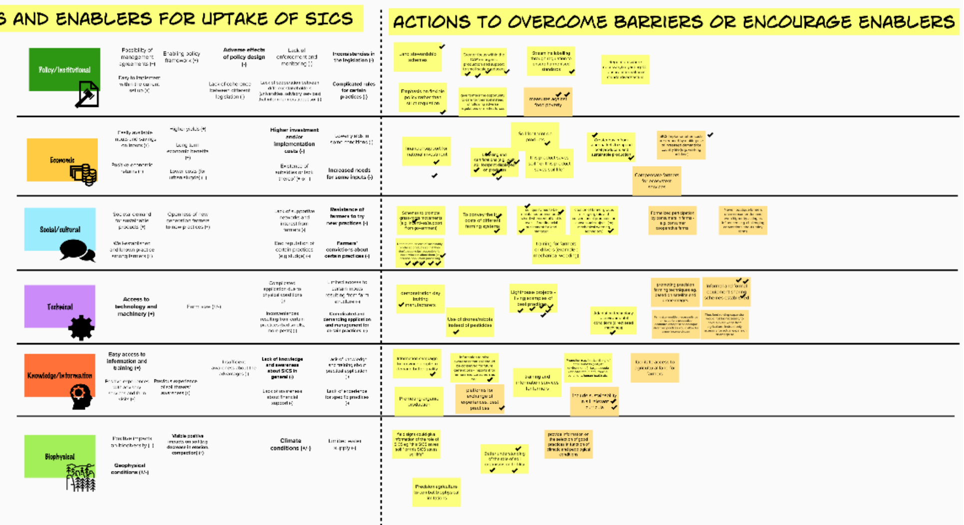
Scenario 1: Local and Sustainable

1

Local and sustainable: individual drive for healthy and sustainable food
Few challenges to voluntary measures, significant challenges to mandatory measures

2

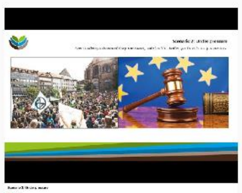
Barriers and enablers for uptake of SICS



Scenario 2: Under Pressure

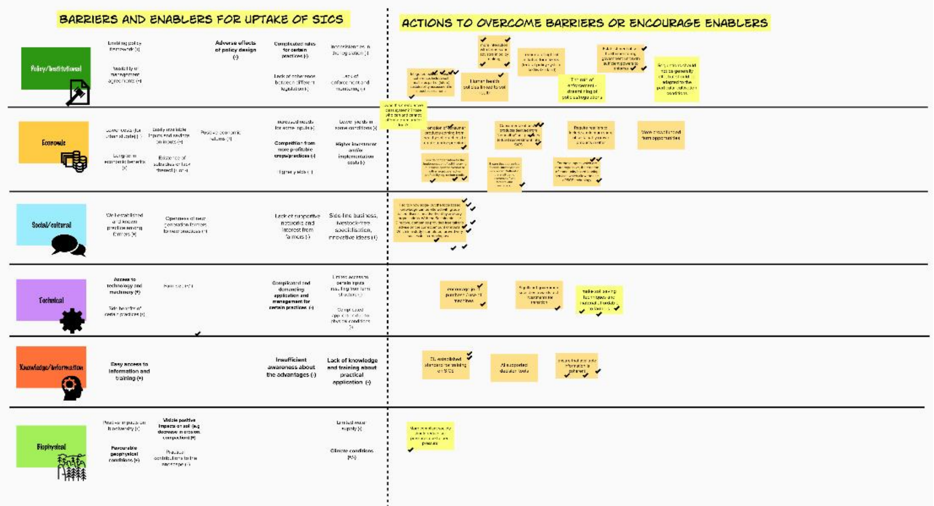
1

Under pressure: Societal pressure for government action
Few challenges to mandatory measures, significant challenges to voluntary measures

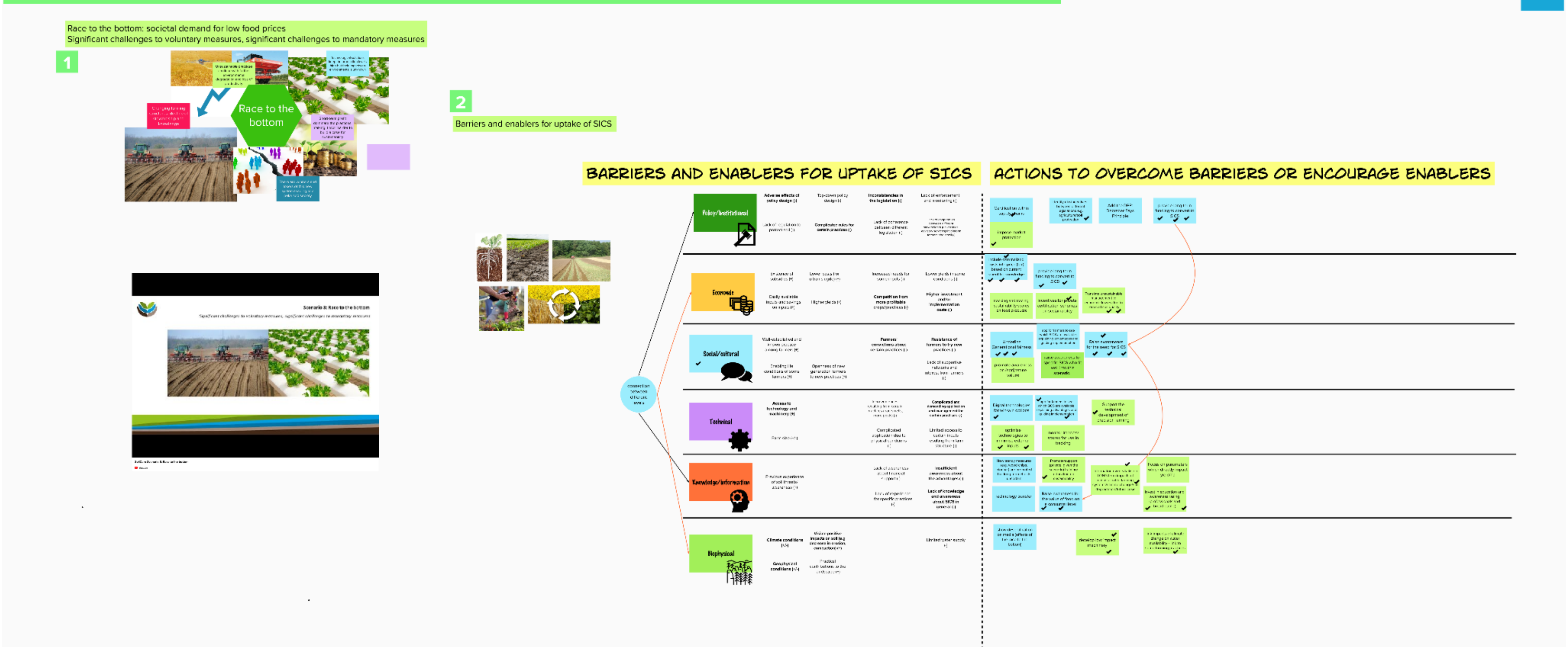


2

Barriers and enablers for uptake of SICS



Scenario 3: Race to the bottom



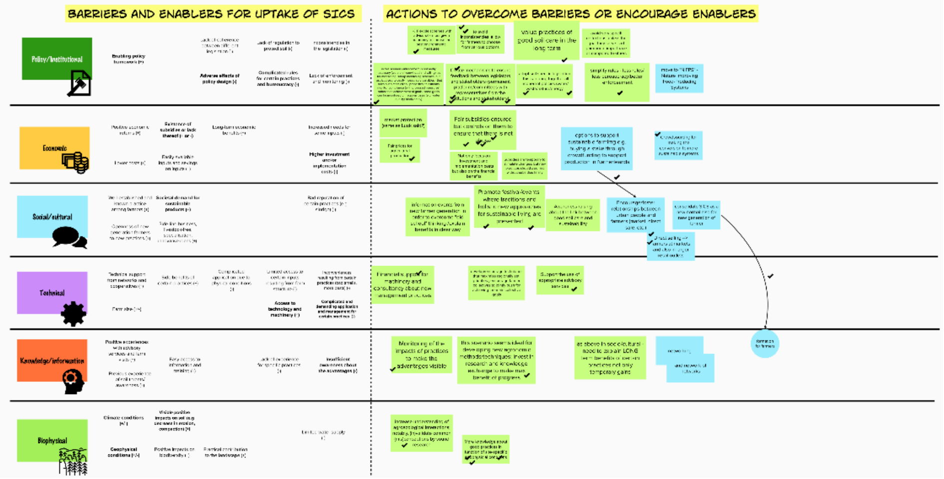
Scenario 4: Caring and Sharing

Caring and sharing: broadly supported resilience approach
Few challenges to voluntary measures, few challenges to mandatory measures

1

2

Barriers and enablers for uptake of SICS



Annex 8: Assessment of success of actions across scenarios

On the next page the format of the exercise 'Rating actions' workshop participants were presented with is presented, together with the results (rating of the actions). As discussed in Sections 4.1 and 4.4, for each selected action, input is provided across all scenarios. Results are further described in Section 4.4.


3
Rating actions
How likely are the actions to succeed under each scenario?
Actions
Under pressure
Societal pressure for government action
Race to the bottom
Societal demand for low food prices
Caring and sharing
Broadly supported resilience approach
Local and sustainable
for those who can afford it
Individual drive for healthy and sustainable food
Challenges for voluntary instruments
Substantial
Few
Challenges for mandatory instruments
Local and sustainable
Under pressure
Race to the bottom
Caring and sharing
Not so likely
Somewhat likely
Very likely
Labelling and certifications (e.g. with soil footprint displayed on products)
Lighthouse projects - living examples of best practices.
Consumer taxation on products derived from "unhealthy" soil practices to fund reinvestment into SICS
Raise awareness for the need for SICS
include externalized costs into price (tax) based on current scientific knowledge
optimise technologies to minimise external inputs
Fair subsidies ensured but controls on them to ensure that there is not abuse
Any other comments?
success may depend strongly of combination of measures

Annex 9: Countries in EU-14 and EU-N13

Countries in EU-14: Austria, Belgium, Germany, Denmark, Greece, Spain, Finland, France, Ireland, Italy, Luxembourg, Netherlands, Portugal, Sweden.

Countries in EU-N13: Bulgaria, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovenia, Slovakia.

Annex 10: Costs of SICS

The next page gives an overview of the cost estimation of the SICS. For further details on the SOILCARE study sites see the Fact sheets on the SOILCARE website and deliverable D5.3: https://www.soilcare-project.eu/downloads/public-documents/soilcare-reports-and-deliverables/184-report-35-d5-3-report-on-monitoring-results-and-analysis-kul-panagea/file

SICS	Case study	Name of SICS	Cost item	Costs (Euro/ha)	Benefits
cover crops	FR	early sowing wheat		-116.9	yield risky
	FR	cover crop maize	CC seeds, less hoeing	77.5	yiel slightly lower
	NO	cover crop for soil health		75.9	also subsidy
	DE	cover crop for glyphosate reduction		267.6	less herbicide
	GR	vetch cover crop in vineyards	inexpensive CC		less erosion, soil healt
	PT	winter cover crop		-49.6	reduced fertizer rate
	ES	deficit irrigation + covercrop + mintill	equipment	180.24	risk higher EC
	BE	grass undersowing	instead f cc	-44	
	RECARE NL			77.95	
	RECARE IT			247	
	UK	*		70.2	
	FR	**		110	
	UK	***		58	
	Overall		Cost: seeds, sowing, elimination; savings: tillage, fertilization, herbicides	**75**	
*	https://www.agricology.co.uk/sites/default/files/NIABTAG%20Cover%20Crops_lowres.pdf				
**	https://orgprints.org/id/eprint/30573/12/Fiches_Especes_EngraisVerts_ENG_2018.pdf				
***	http://www.cccagronomy.com/articles/a-guide-to-growing-cover-crops				

minimum tillage	CH	green manure and minimum tillage		-20.2	less herbicide
	CZ	minimum tillage	red tillage	-39	SOC, yield increase
	BE	strip tillage		-48	reduced yield
	GR	notill			less erosion
	IT	conservation tillage		-143	yield increase, risk crop failure
	HU	reduced tillage	more chemical control	36.8	higher yield
	RECARE IT	conservation agriculture		20.75	
	UK	*		-55.0	
	UK	**		-70.2	
	UK	***		-93.6	
	Overall		Cost: generally saving on tillage operations, in systems may lead to other costs (e.g. herbicides)	**-50**	
*	https://s3.eu-west-2.amazonaws.com/assets.theriverstrust.org/Legacy-uploads/Pinpoint-23.0-Cultivation-techniques-to-protect-soils-Minimum-tillage.pdf				
**	https://www.agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf				
***	https://s3.eu-west-2.amazonaws.com/assets.theriverstrust.org/Legacy-uploads/Pinpoint-24.0-Cultivation-techniques-to-protect-soils-Direct-drilling.pdf				

compaction reduction	NO	deep-rooting cover crops		-463.8	cover crop not easy to sell
	UK	deeprooting grass ley	similar	0	
	UK	notill for compaction reduction (sub-soiling)	subsoiling	35.2	yield increase
	RO	tillage/subsoiling		573.0	substantial yield increase
	SE	straw in upper soil (for compaction alleviation)	subsoiling		
	RECARE DK	preventing soil compaction		279	
	Overall		Costs: subsoiling, seed/sowing deep-rooting crops; savings: other type of tillage	**75**	

mulching	BE	wood chips	wood chips (for 3 y?)	667	infiltration rate
	HU	organic fertl - straw	farm yard manure	25.6	SOC
	RECARE ES		straw mulch	250	
	UK	*		276.9	
	Overall		Cost: mulching material, application/incorporation (assumed once in 3 years)	**250**	
*	https://www.organicresearchcentre.com/wp-content/uploads/2020/12/WOOFS_TG1_Final.pdf				

Figure A10.1. Overview of case studies of different examples of SICS and overall cost estimates for each SICS type used in the integrated modelling.