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SUSTAINABLE PLANT PROTECTION TRANSITION

Report on regional impacts of different ranked PPP reduction scenarios

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1. Introduction

This deliverable describes the results from modelling a number of scenarios of reduced pesticide use in the case study regions in Slovenia, France and The Netherlands, as described in Deliverable 6.4. The aim of this modelling is to illustrate how scaling up various pesticide reduction strategies would impact overall food supply, health and environmental impacts, as well as economic performance, and which trade-offs and synergies may arise. Due to the nature of such modelling, a less detailed but more encompassing approach than in the case studies is needed, as the goal is not to identically replicate the case study farms to cover a much larger land area with a much larger number of farms that are identical to the case study farms. The goal is rather to identify the common core aspects and principles of the pest reduction strategies pursued in the case study farms (namely agroecological practices such as wider crop rotations and mechanical weeding; organic production; choice of robust varieties and changes in fungicide application strategies for reducing fungicide residues) and to model the effects of a much larger areas in the region being managed according to these core principles.

This approach naturally results in a reduction of details when compared to the information available on the single farms. Scaling the pesticide use reduction strategies to larger areas according to the underlying principles of these strategies cannot capture a single farm in detail but it can rather on average capture a larger number of farms pursuing the same strategies; or, framing it differently, it can capture the landscape-level consequences of the application of the pesticide reduction strategies on a larger area covering many farms in a landscape. On the other hand, this approach pursued in the modelling work results in some enrichment of strategies, when compared to the single farms, as the upscaling needs to be embedded in a broader development in the region that makes sense beyond farm level and that thus reflects the implementation of the core principles of the pest reduction strategies also in other aspects of agricultural land management and food system design.

The reduction in details affects which information on single pesticide use and impacts and related benefits and costs (e.g. in reduced yields or increased labour costs) from pesticide use reductions on farm level can be used in the modelling, as the farm-level information is too detailed and specific to serve as a basis for upscaling on regional level. Thus, more aggregate indicators are needed, and rather than assessing plot specific pesticide use for a single farm as a basis for modelling, we build on the broader aspects of the strategies pursued on the single farms, e.g. captured in risk indicators (for yield loss, health impacts, for example) or average impact values together with some distribution of uncertainty. The enrichment of strategies, on the other hand, allows to discuss the pesticide reduction strategies and their impacts and consequences in a broader context of agricultural land management and food systems design, thus allowing to link the farm level actions to the societal level.

A central indicator for assessing the pesticide use reduction strategies is the yields that can be realised with their application. Ideally, pesticide reduction would be implemented without yield gap, but in reality, this is difficult to achieve and in general, considerable yield gaps may result from the reduction of pesticide use. Thus, pesticide reduction is never implemented by just reducing pesticide inputs to meet a certain target such as e.g. 25% lower pesticide use levels, but it is implemented in the form of strategies to counteract this potential drop in yield that comes with the pesticide use reduction. This combination of pesticide use reduction plus complementary activities are then exactly the pesticide use strategies investigated. These strategies can encompass various agroecological farming practices such as changed weed management or crop rotations, or the choice of resistant varieties, for example. For implementation in the model, these different practices chosen for complementing pesticide use reduction are the starting point. It is then decided to which extent (e.g. on which share of areas) a certain practice shall be implemented and in consequence, it is assessed which reduction in pesticide use may result from this, and which yield gap may materialise as a consequence of the pesticide use reduction, complemented with and thus counteracted by the specific practices of the strategy.

Next section describes the methodology used for the scenario modelling. The section contains the description of the model used, various scenario dimensions investigated and the resulted indicators. Sections 3 and 4 present and discuss the results of the modelling runs and we finally concluded in section 5.

2. Methodology

In this section we describe the methodology used. First, the SOL model which is used for the scenario modelling is presented, followed by a description of the scenario dimensions and indicators.

2.1. The SOL model

SOLm is a mass- and nutrient-flow model of the food system, covering plant and animal production. It thus traces all mass and nutrient flows through the food system, from the inputs to agricultural production to the emissions from food waste disposal, also covering the linkages between crop and livestock production via feed and manure. Here, we describe first the model in its general terms and then shortly explain some specific aspects of it that are also central for the modelling work in the SPRINT project.

2.1.1. SOLm – general description

The basic structure of SOLm is captured in the following Figure 1 and Figure 2. Starting from a certain area for agricultural production cropped with a number of crops or managed as grasslands, the corresponding outputs are derived, comprising main outputs such as grains but also by-products such as residues. These outputs are then exported from agricultural production and processed along the commodity tree into various commodities to be used finally as food, as feed for animal production, otherwise (e.g. for fibre or bioenergy), or they are recycled to the agricultural areas (e.g. as residues left on the field). Together with other inputs (e.g. mineral fertilizers, pesticides) and all emissions and impacts from the production activities, all this captures the land use/plant production part of the model. Animal production is captured similarly, tracing the flows from feed from croplands and grasslands to outputs from animal production systems. Part of the outputs are recycled to animal production (e.g. whey from cheese production fed to pigs), part is used in crop production (e.g. manure), and part is exported from agricultural production to be used as food or otherwise (e.g. wool). Together with other inputs (e.g. antibiotics, drinking water for animals) and all emissions and impacts from the animal production activities, all this captures the animal production part of the model. The nutrient flows in feed and manure link animal and crop production and all these parts together describe the production part of SOLm.

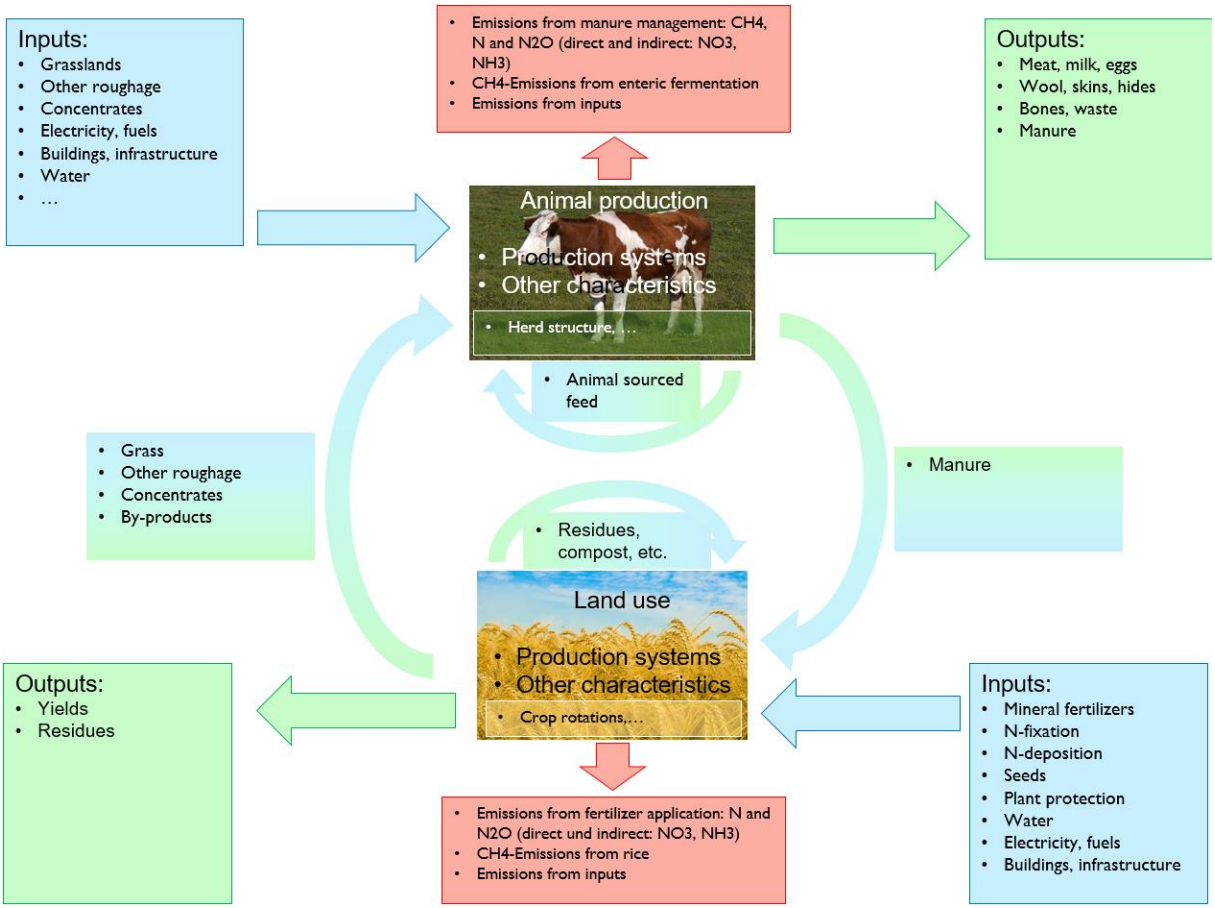

Figure 1: Structure of the biomass and nutrient flows on production level in the SOL model

The calculations thus capture the agricultural areas and the number of animals and the related inputs, emissions, impacts and outputs in each geographic region of interest. Inputs can thereby also be imported from outside the systems, and impacts can also become relevant outside the system. This is then better captured by adopting the food-system view on the SOL model, schematically displayed in Figure 2, which is complementary to the production-focus just presented above. In the food-system view, the mass and nutrients flows are traced starting from the "domestically available quantity" of commodities. This quantity stems from domestic plant or animal production (depending on the commodity) and from imports and stock changes, while exports or allocation to building up stocks reduce the domestically available quantity. This domestically available quantity is then used for various utilizations such as "food", "feed" or also "waste" or "bioenergy" (here in Figure 2 captured via "other"). The share used for food determines the food availability (which food, as said, stems not only from domestic production within this region but also from imports or stock changes), captured by physical quantities but also by macro- and micro-nutrient supply, such as calories, proteins, vitamins, etc. The share used for feed determines how much feed is available for animal production within each geographic region (which feed, again, stems not only from domestic production within this region but also from imports or stock changes). Finally, as already indicated in the production view above, both plant and animal production result in a number of emissions and impacts, which – in the food systems view – are seen as emissions and impacts from (different parts of) the food system.

We emphasize again that the focus of SOLm is on biophysical and agronomic mass and nutrient flow modelling, hence focusing on environmental impacts, as displayed in the figures, with socio-economic indicators such as labour use, costs or labour productivity thus only being added at the end of the

calculations on the basis of simple impact factors per hectare land, ton of product or animal head, as these are not part of the core modelling (cf. section 2.1.3).

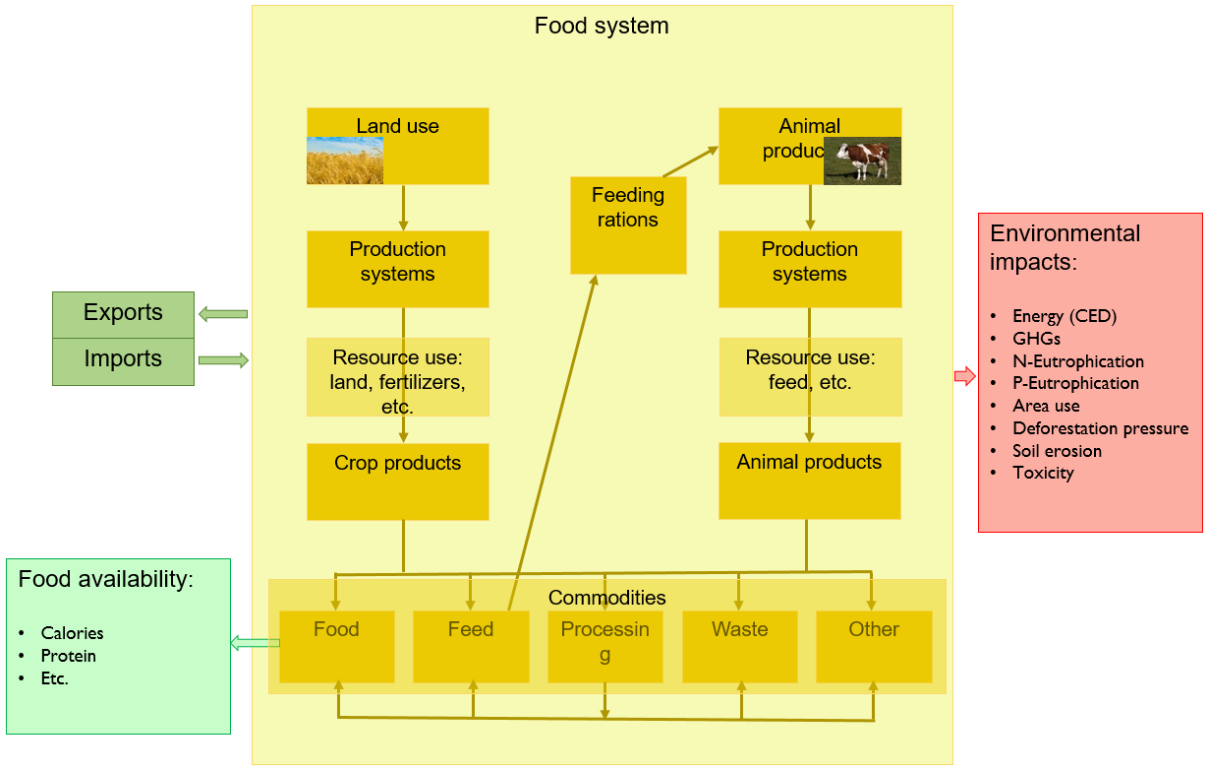

Figure 2: Structure of the biomass and nutrient flows on food system level in the SOL model

This combined land use/plant-animal production system is located within geographic boundaries – the default is country level, but provided adequate data is available, it can be refined to arbitrary sub-country levels. The results from the calculations can then be aggregated to country groups, world regions or a global picture.

Key entities in SOLm are "**production units**", "**commodities**" and their "**utilization**" as well as "**processes**". Production units are the key producing physical units (ha of cropland, a producing animal with its herd, a volume of aquaculture, etc.) together with the required actions, technologies, transformations that produce a number of outputs from a number of inputs, thereby also causing emissions and other sustainability impacts. Production units have an internal structure, e.g. some information on the relation between different parts of a crop rotation or, for animal production units, the herd structure. Inputs to production units are e.g. fertilizer, feed, plant protection means, energy, water, etc. and outputs are all biomass that is immediately produced from a production unit. For a hectare of wheat, this is the wheat crop including belowground and aboveground biomass, for a dairy production unit, it is the milk, manure, the cow that is then slaughtered at end-of-life and a calf per lactation, etc.

The outputs from the production units are a subset of all commodities in the model. Commodities thus cover the whole wheat plant, and also the wheat grains, wheat straw, leaves and the roots of the wheat plant, into which the whole plant biomass is separated into. Those commodities are then partly processed further, e.g. wheat grains into flour, bran and germ, etc. This structure is captured by the commodity trees that indicate which processes produce which commodities as outputs from which commodities as inputs (e.g. the process "wheat flour production" produces "wheat flour", "wheat bran" and "wheat germ" from "wheat grains". Commodities are thus the physical outputs from production units plus commodities derived via processes along the commodity tree, where the processes thus describe how outputs are

generated from production units and how commodities are transformed into other commodities along the commodity trees. Two central parameters govern the commodity trees, namely the commodity tree share and the extraction rates. The commodity tree shares indicate which share of a commodity is processed in which process (e.g. how much of wheat grains go into flour making, how much into cereals, how much are used as grains, how much are processed as beer, etc.). The extraction rates indicate which part of a commodity entering a process results in a certain output, i.e. which percentage of wheat grains entering the process wheat flour making ends up as flour, which as brans and which as wheat germs.

Finally, commodities are then "utilized" for various uses, such as food, feed, energy, waste, etc. This is based on the domestically available quantities (DAQ) that are derived by adding commodity imports to the commodity production and by subtracting commodity exports from those, as well as to account for commodity stock changes.

With this structure, SOLm thus offers to investigate the impacts of changes on the production level (e.g. choices of crop rotations and assumptions on yields with pesticide use reduction) on the whole food system level, captured by food and other commodity provision as well as input use and environmental impacts.

2.1.2. Decision structure in SOLm and the principle of "ceteris paribus"

SOLm does not have an internal decision structure for decision making units (such as e.g. country-wise or global utility maximization in economic models or greenhouse gas minimization as an environmental goal, etc.). It is thus driven by the explicit exogenous assumptions set by the researchers running the model. In the most common scenario specification in the model, these assumptions have to be quantified by the amount of area cropped by each crop and grassland type of relevance in each geographic region. Given this input, and a number of other assumptions that are provided as defaults or are also to be chosen by the researchers in the scenario specification, the model runs to derive plant production, feed use and related animal production, total food availability, waste and other utilization (e.g. bioenergy) and all related emissions and other impacts.

Given the absence of an internal decision structure for decision making units, the general philosophy in SOLm is to adopt a "ceteris paribus" approach, i.e. an approach that "keeps all else equal - or as close as possible" (to some baseline or reference situation) besides some core changes of central interest for a specific scenario. That is, besides the "core changes of central interest for a specific scenario" the approach is to keep this "number of other assumptions that are provided as defaults or are also to be chosen by the researchers in the scenario specification" mentioned above as close as possible to some baseline or reference situation, unless the research question to be addressed in a specific scenario forces to do otherwise. Thus, the relative shares between areas for different fruits or vegetables or between chicken and pig production, for example, are assumed to be identical to the reference situation when investigating a shift towards full organic production or reduced concentrate feed use, unless some explicit assumption on those crops or animals is made that requires different assumptions (e.g. when combining organic production with specific assumptions on which crops are particularly difficult to be produced in this production system (such as e.g. sugar beet or rapeseed), the area shares of those are adjusted in favour of roots and oil-seeds that are easier to produce in organic production).

Often, models with an endogenous decision structure are deemed to be more realistic than such exogenously driven models such as SOLm, as the former consistently cover this decision making part of the system based on some underlying societal or psychological theory. However, these models with decision structure also depend on strong assumptions, such as, for economic models, on price elasticities determining how much demand changes with changing prices, or cross-price elasticities determining how much substitution occurs between commodities when their relative prices change. These assumptions are however rather hidden in the model details and not as explicit as the assumptions made exogenously in

models such as SOLm. This data (e.g. on elasticities) is by far not always available and often assumptions on the values of these elasticities have to be made on a thin or missing empirical basis. Furthermore, the type of questions addressed with SOLm (primarily large changes, cf. section 2.1.3) often cannot be addressed well with such models with endogenous decision structure, as the decision structure is calibrated with observed situations and how such decision structure may change with drastic deviations from these calibration points is most often unknown. Economic food system models, for example, are calibrated at the point of (an enforced) general market equilibrium and are most valid in a range around this point, losing validity the further off one may move from this equilibrium in a scenario, as no information is available on how preferences and elasticities may change with such large deviations. Thus, such economic models can well capture effects of an increase of organic production from an observed 15% share to 17% or 20%, or also a decrease to 12%, - but they have not a better empirical basis to answer changes towards 50, 80 or 100% organic production than the models with exogenously given assumptions such as SOLm. Hence, the absence of an endogenous decision structure is not a general disadvantage for the types of questions addressed with these models (see section 2.1.3).

We particularly highlight the difference of models without optimization as a proxy for endogenous decision structures, such as SOLm, to models with such optimization structure. The latter e.g. optimize cropping patterns subject to certain goal functions and boundary conditions, while SOLm starts from a reference situation and derives the scenario implementation in close connection to this. Thus, results from optimization in general display the potential that could be achieved in a world where agriculture and the food system is organized optimally regarding the goals addressed and the aspects covered in the model, while SOLm pays more credits to observed regionally differing production and consumption patterns and trade-flows, thus capturing a more "realistic" world (in the sense of being closer to observed production, trade and consumption patterns) at the cost of not being able to optimize. In this, the results from both these model types complement each other, by indicating the potential of an optimal organization of the system on the one hand contrasted to a less optimal organization that in exchange captures better current national peculiarities of agriculture and the food systems.

Some remarks are in place; first, without optimization, corner solutions are avoided, that often arise in optimization scenarios, when one activity is more efficient than all others (e.g. wheat is more efficient in calorie production than barley or oats) thus resulting in only the most efficient activity being chosen while all others are being set to zero. This can be avoided by adding boundary conditions of minimal area shares or such, but this then adds social-planner aspects to the optimization scenarios and contrasts with their core rationale and advantages. Second, investigating the option space of a large number of different parameter combinations (cf. section 2.1.4) also allows to identify multiple (local) optima, in case such are present, a situation the optimisation models usually do not test for. Finally, some intermediate approach may be mentioned, if optimization models minimize the "distance" to a reference situation (e.g. regarding dietary patterns or cropping patterns - e.g. via minimizing the sum of the squared differences between the per-capita consumption of each commodity in the reference situation and the scenario) conditional to certain levels that should be reached (e.g. not more land use than in the reference situation or not more GHG emissions than 70% of the reference situation, or such). Such approach is still based on optimization, but the story behind is not an optimization regarding environmental impacts, but rather a way to endogenously capture the aim to "keep all else equal - or as close as possible (to some baseline or reference situation)". In this, such approach does not combine both approaches and their respective advantages still prevail.

2.1.3. Which questions can be addressed with SOLm?

SOLm is most adequate to address large changes in the food system and in agriculture with respect to some baseline or reference situation. This is due to its global scope and the default country level resolution of the data used. Further differentiation is always possible, given due data is available, but generally, even with some sub-country regionalization and some differentiation between crop varieties, for example (e.g. winter vs. summer wheat), the results remain on a comparably aggregate and gross

level. Thus, given the generally large uncertainties or gross averages and aggregations in the data used, results from SOLm are most helpful when comparing large changes such as a conversion to 30, 50 or 100% organic production rather than smaller changes going from 15 to 17%. In models such as SOLm, results from such small changes generally will be overshadowed by data uncertainties and error margins. Given all the uncertainties in the data, it is also often more illustrative to assess relative changes between different options than absolute values.

Examples of questions that are addressed with SOLm are thus the conversion of a significant share or 100% of production to organic agriculture, the shift towards zero food-competing feed use (i.e. abandoning concentrate and forage feed specifically cropped on cropland, where food crops could be grown directly), or a shift towards a healthier composition of food baskets. Often such situations involve quite drastic changes in production and consumption patterns and are thus understood as investigations into food systems in the farther future, say in 2050 or 2100, then also using reference scenarios for the same time-scales, such as FAO or IPCC projections for 2050 (e.g. regarding population numbers, economic development, etc.). However, counterfactual analysis of the current food systems are also possible, e.g. by investigating a situation of 100% conversion to organic agriculture for a specific region or for a national food systems, thus using the current situation as a baseline for comparison. In fact, due to historical data from FAO being available in the model, it is in principle also possible to investigate counterfactual situations for past time periods. Generally, the term "baseline" is used to refer to one year or to a several-year time-period representing the "current" agriculture and food system. Due to data availability, this lies often some years in the past. The term "reference scenario" is used for a hypothetical, often future, situation, which can be considerably different from the situation today, e.g. a projection for the food system in 2050 as provided by the FAO. In the model runs, further hypothetical situations of the food system are then calculated and compared to the baseline or the reference scenario, depending on the context the calculations refer to (e.g. a counterfactual to a current situation or an alternative for the 2050 business as usual food system).

Regarding results, a particular focus of SOLm is to analyse trade-offs and synergies between different indicators for various options or scenarios (cf. section 2.1.4), or between different strategies or changes with respect to certain indicators, and thus to identify potential options where particular challenges for implementation may arise, or to identify options that are particularly promising. Thus, SOLm results on a large-scale conversion to organic agriculture, for example, illustrate potential trade-offs with sufficient nitrogen supply, and the results on food-competing feed reductions illustrate how drastic the changes in animal source food supply may become and how large changes in animal source food consumption thus may need to be to make such a change in feeding practices and the corresponding implementation of more circular food-systems a widespread option (Schader, Muller et al. 2015, Muller, Schader et al. 2017).

It is important to note that any baseline or reference situation with adequate data availability can be chosen as point of comparison for the options calculated with SOLm. Thus, SOLm results can provide insights on counterfactual situations to the current (or also past) food system, or insights on different options in comparison to, for example, the FAO projections for 2050 from 2012 (Alexandratos and Bruinsma 2012) or in comparison to each of the three updated FAO scenarios for 2050 from 2018 (FAO 2018), or in comparison to the scenarios used in the IPCC report on the 1.5 degree goal (IPCC 2018), etc. If not yet available in SOLm, data for such reference scenarios can be added relatively easily.

Given the absence of any societally or psychologically motivated endogenous decision structure, the results generated by SOLm primarily provide information on the biophysical and agronomic viability of food system options and scenarios with respect to certain biophysical, agronomic or political (or other) restrictions that can be translated in limit or target values for the performance indicators provided by SOLm. The results do not address the socio-economic viability of these options or scenarios in the context of some socioeconomic, psychological or other societal theory. This additional context then

provides further restrictions to the viability of options, which are outside the scope of the topics that can be addressed with SOLm. SOLm thus provides a basis for such further assessments and discussions, the main contributions being information on trade-offs and synergies related to different options and indicators and on the options' biophysical and agronomic viability, or their viability regarding some environmental targets. If the latter is not given or very challenging, for example, it can be derived that any further analysis of the respective options may not be needed as these options would anyway be unrealistic due to biophysical or agronomic reasons or due to not reaching certain environmental goals.

We may mention, though, that some simple analysis of socio-economic and such indicators is possible, if values for such are available on the level of quantities, production unit numbers (e.g. areas, animal numbers) or processes, for example. In this case, some price information multiplied with commodity quantities allows a gross assessment of potential revenues or costs, similarly for costs of inputs or impacts (e.g. using the social costs of carbon mutliplied with GHG emissions). Another example would be labour demand per production unit - for an assessment of overall labour demand, or, in relation to commodity prices, for an assessment of labour productivity. Like this, a number of indicators of broader societal than mere biophysical or agronomic relevance may be added to the model. If used with due caution, such results can complement the biophysical assessment by important aspects. Most central, thereby, it has to be kept in mind that with such a use in SOLm, these unit-indicators (e.g. price per quantity, labour input per area, etc.) do not react to changes of the system and context and are thus not reacting to likely changes in markets, for example, e.g. in the case of a large-scale switch to organic agriculture that likely would result in price increases, thus disrupting a price and cost analysis based on currently observed prices.

2.1.4. Option space, viability and scenarios

The results from the model runs can be framed by the notion of the "**option space**". Assume that we investigate, for example (as done in Muller, Schader et al. (2017)), the consequences of a conversion to increasing shares of organic agriculture, combined with different levels of food-competing feed reduction and different levels of food waste reduction, all assessed in a context of increasingly strong climate change impacts on yields. The reference scenario for this example is the FAO business as usual projection for 2050 from 2012, as described in Alexandratos and Bruinsma (2012). The results of all these changes can be framed by the various combinations of different parameter values along these four dimensions (each one combination providing one "option" for the future food system) as displayed in Figure 4, employing the example of "percentage change in cropland use with respect to the reference situation" as an impact indicator (dimension 1: shares of organic production of 0, 20, 40, 60, 80, 100%; dimension 2: food-competing feed reduction by 0, 50, 100%; dimension 3: food waste reduction by 0, 25, 50%; dimension 4: climate change impact on yields resulting in yield increases till 2050 being reduced by 0, 50, 100% with respect to the reference forecasts). Figure 3 thus displays the "option space" for global cropland use of the combinations of changes along these four dimensions which can then be assessed to identify promising options (with strongly reduced land use) and rather negative options (with strongly increased land use).

In short, **the option space is the totality of all options that emerge from combining different levels along a number of different key dimensions describing a food system of interest that are varied to explore the potential future or counterfactual to a baseline or reference scenario of this food system** (in the example above: share of organic production, food-competing feed reduction, wastage reduction and climate change impact on yields, and all this is assessed for the global food system).

It has to be emphasized that the aggregation to global levels as done in this example potentially hides important regional patterns, as situations could arise, where additional local land use would be prohibitively high albeit total land use would decrease globally. SOLm however provides the data needed

to also assess this, as it basically works on country (or – depending on data availability – even finer) level.

% Wastage reduction	% Reduction in food-competing feed	Climate change impact on yields: Zero – % Organic 0	20	40	60	80	100	Medium – % Organic 0	20	40	60	80	100	High – % Organic 0	20	40	60	80	100
0	0	0	5	10	17	25	33	21	26	33	40	47	57	46	50	54	58	64	71
	50	–16	–12	–8	–4	2	8	2	7	10	16	22	27	25	26	29	32	35	40
	100	–26	–24	–20	–16	–12	–8	–9	–6	–3	1	5	9	12	13	14	15	17	20
25	0	–6	–1	5	10	18	26	14	20	25	32	40	48	39	42	45	50	56	61
	50	–22	–18	–13	–8	–4	–2	–4	0	5	9	14	21	18	20	22	25	27	32
	100	–30	–27	–25	–21	–17	–13	–14	–11	–8	–5	–1	4	6	7	8	8	10	13
50	0	–11	–7	–1	5	11	20	8	13	18	25	32	40	30	34	38	42	47	53
	50	–25	–23	–19	–14	–9	–4	–9	–6	–2	3	8	14	10	12	15	17	21	25
	100	–35	–32	–29	–25	–22	–18	–19	–17	–13	–10	–7	–3	–1	0	1	3	4	7

Figure 3: Example of an option space as the result from SOLm model runs (Source: Muller, Schader et al. 2017); Original Figure Caption: Cropland area change. Percentage change in cropland areas with respect to the reference scenario. Scenarios differ in: organic shares (0–100%), impacts of climate change on yields (low, medium, high), food-competing feed reductions (0, 50, 100% reduced from the levels in the reference scenario), and wastage reduction (0, 25, 50% compared to the reference scenario). Colour code for comparison to the reference scenario value (i.e. 0% organic agriculture, no changes in livestock feed and food waste, dotted grey): > +5%: red, < −5% blue, between −5% and +5% yellow; in the reference scenario, cropland areas are 6% higher than in the baseline today.)

The option space can be provided for any indicator of interest, such as, besides "cropland use", greenhouse gas emissions, nitrogen surplus, deforestation pressure, aggregate eco-toxicity, erosion risk, etc. When displaying an option space for a number of parameter combinations for one indicator, the notion of "viability" of an option (i.e. of a combination of certain parameter values) is also helpful in analysis and communication. "**Viability of an option**" refers to the performance of an option, i.e. the corresponding indicator value, in relation to some general external restrictions, that can be biophysically mandatory (e.g. global potential cropland area is physically constrained and any option resulting in a larger global land use than this upper limit is biophysically impossible, i.e. unviable) or (politically highly) desirable (e.g. related to planetary boundaries on greenhouse gas emissions, deforestation or nitrogen surplus for a safe operation space of humankind, and any option that would e.g. conflict with some deforestation reduction targets or with limiting global warming to 1.5 degrees would thus also have to be termed "unviable". This judgment would however in this case not be based on biophysical terms but in relation to the goal to not transgress these boundaries for a safe operation space for humankind).

The option space in principle also allows to identify areas of optimal, maximal or minimal performance, i.e. searching for the type of results that are commonly produced by optimization models. In this, SOLm and its option spaces will not allow to exactly find the optima, but the rough area in the option space where optima can be found, which is specific enough given the huge uncertainties and large numbers of assumptions necessary in such modelling. Furthermore, investigating the option space also allows to identify multiple (local) optima, in case such are present, a situation the optimisation models usually do not test for.

Finally, a third term is often used in the context of option spaces and viability of options, namely "scenarios". In this context, we use scenarios to describe certain options or groups of closely similar options which we amend by a detailed description of which socio-economic and cultural, etc. dynamics may drive them, e.g. regarding the context of policies, peoples' preferences and values, economic development etc. without explicitly including this additional information in the model. Scenarios **are thus telling the rich societal, economic, psychological and value-related (i.e. ethical) stories or narratives behind a special option or behind a sub-set of similar options in the option space**.

2.2. Scenarios and baseline

In Deliverable D6.4 (Meier et al., 2024b), a number of scenarios have been identified as basis for the modelling calculations. These scenarios are based on the results and data from the case studies and represent a selection of pesticide reduction strategies where upscaling to regional level can be modelled, for illustration of the impacts of large-scale implementation of such pesticide reduction strategies. For such further analysis, seven scenarios have been chosen, two each with a country and crop-specific regional focus, namely silage maize in Slovenia, vineyards in France and seed potatoes in the Netherlands, and one with a much more aggregate focus on the level of the whole EU food system. Each scenario is implemented via two or three dimensions that then span the option space for this case, cf. the following Table 1. Generally, for the country-related scenarios, the first scenario implements a number of agroecological practices as one dimension, while the second scenario implements conversion to organic production. The different scenario dimensions are described in more detail in the next section 2.3. More details on the identification of these dimensions and some further contextualisation and discussion of those are available in deliverable D6.4 (Meier et al., 2024b).

Case	Scenario	Dimension 1	Dimension 2	Dimension 3
Silage maize (Slovenia)	1.1	Agroecological measures		Rainfall intensity
	1.2	Organic share	Reduced feed-food competition	Rainfall intensity
Vineyards (France)	2.1	Low residue strategy	Robust varieties	Rainfall intensity
	2.2	Organic share	Robust varieties	Rainfall intensity
Seed potatoes (The Netherlands)	3.1	Agroecological measures	Robust varieties	Rainfall intensity
	3.2	Organic share	Robust varieties	Rainfall intensity
Agroecological and pesticide-reduced food systems in Europe	4.1	Organic share	Various aspects as detailed in INRAE 2023	Rainfall intensity

Table 1: Scenario dimensions for the country-specific SPRINT scenarios

For each case, a specific baseline is identified, as described in Deliverable 6.4. This is a business as usual (BAU) scenario, detailed as follows (Table 2):

Case	Description of the baseline (BAU)
Silage maize (Slovenia)	IPM production of silage maize for cattle (almost 100% of farms conventional[1]); use of synthetic herbicides for weed control (mainly 1 treatment/ year with a more or less toxic synthetic herbicide to control annual weeds – a lot of emphasis is put on the timing of application – and 1 treatment in 5 years with Glyphosate, to control perennial weeds); minimal mechanical weeding (e.g. once before seeding); minimal crop rotation with grass-clover mixture once in five years – but at least 3 crops (silage maize 3 times, grass-clover mixture once, cereal once); cover crops in winter.
Vineyards (France)	IPM production (88%); planting density: 1.50 to 2 metres between rows (narrow); first fungicide treatment in growth stage BBCH15, and on average a total of 13 chemical fungicide treatments (against powdery and downy mildew). A treatment can include more than one fungicide product and 15 different products were used 10 synthetic and 5 organic). Out of the 13 treatments, 8 treatments used synthetic and 9 organic fungicides. Thus, 4 treatments used only synthetic and 5 only organic products.
Seed potatoes (The Netherlands)	Conventional production; crop rotation width: 1:3; other crops included in the crop rotation: barley, wheat, sugar beet, onions; about 8 to 10 PPP treatments with 3 to 5 synthetic fungicide s (no non-synthetic fungicides used); buyer: large traders (also for export); yield: 30 to 40 tons/ha; generally seed potato farms are growing in size – the largest farms ranging between 400 and 500 ha (Small farms usually lease their land to larger farms in the year when seed potatoes are grown); which varieties and for how long a variety is grown very much depends on the offer and demand on the side of seed potato traders with whom seed potato growers have contracts; generally a farm grows 8 to 10 varieties or more and each variety for 3 to 8 years.
Agroecological and pesticide-reduced food systems in Europe	As detailed in the report INRAE 2023, section 5.2, specifying assumptions on: - Population growth - Diets - Crop yields - Animal feed efficiencies - Cropping intensities - Maximum cultivable areas - Trade parameters - Non-food use of agricultural products

[1] For D6.1, 12 Farms have been analyzed (6 organic, 6 conventional). 7 (1 organic and 6 conventional) out of these 12 farms produced silage maize and were therefore considered in D6.4. Additionally, 15 farm observations were provided after the submission of D6.1. For 13 (all conventional) out of these additional 15 farm observations environmental and health impact and damage costs could be inferred from D6.1 results. Hence, 20 farm observations has been used in D6.4, whereof 19 are conventional, 1 organic.

Table 2: Baseline scenarios for the different cases

The data available from the case studies is primarily collected at farm level, capturing the current situation on the case study farms (mainly quantitative), complemented by information from expert interviews on the potential of the various pesticide use reduction strategies (mainly of qualitative nature), c.f. Deliverable D6.3 (Meier et al. 2024a) and the database Mark et al. (2024a) as well as the related paper Mark et al. (2024b). Partly, the case study farms also provide information on farms that could be present in the scenarios, such as e.g. organic farms. These farm samples from the case studies provide an illustrative picture of those cases, without being representative for the region or the country. Hence, we decided to implement the scenarios (inclusive baseline) in a correspondingly illustrative manner, assuming that the total area of the key crop in the case study region (silage maize for Slovenia, vineyards for France, seed potatoes for The Netherlands) is managed according to the farms operating according to the baseline assumptions and then capturing the scenarios by the assumptions on areas/crop rotations and management made further down (cf. Table 7), implicitly assuming corresponding changes on farm-level and on the level of farm types and the various areas related to those. As just mentioned above, for some of these changed farm types, some information can be taken from the case study data (e.g. for change to organic production in a case where a number of organic farms are covered in the sample). For others, they have to be defined based on assumptions that will be detailed in the following. Most important, the direct reference to the farms of the case studies allows to directly link the baseline to the reported impacts on human health, ecosystem quality and resource use. Ideally, by using suitable farm designs in the scenarios, these impacts can be adjusted to deliver corresponding indicator values for the scenarios as well. Working on farm level as the basis here is also advantageous, as it allows to capture the impacts of the land management across all crops, including those not being in the focus of the case study, embedded in the context of functioning farms. Furthermore, impacts on outputs can be assessed in a farm context (e.g. regarding changes in feed provision for the cattle on the silage maize farms in the Slovenian case study) as well as more aggregate (e.g. regarding total food output from the total crop rotations).

For all scenarios, we assume that a total of 1000ha being cropped according to the various scenario assumptions on crop rotations and management.

For all detailed numbers on the farms, crop rotations and scenarios, please refer to the separate excel-file "sprint_d6_5_croprotation_impact_scenario.xlsx".

2.2.1. Silage maize in Slovenia

The baseline is characterised by conventional silage maize production and minimal crop rotation with grass-clover mixture once in five years – but at least 3 crops, i.e. as realised by farms F10, F13, F14, F15, F16, F19 and F25 in the case study in Slovenia (cf. the following Table 3 below from Deliverable D6.3 (i.e. Table 2 in Meier et al. 2024a)), with the relevant farms highlighted.[2]

For Slovenia, the baseline is calculated by allocating the total area to the crop rotations covered by the farms listed in Table 3 in proportion to their farm size, or, for simplicity, with an equal allocation of one

[2] Some uncertainties however arise on whether there are 12 farms and 24 fields (what we would expect based on the database Mark et al. (2024a)) or whether there are 24 farms (as reported in D6.3); similarly, numbers on average areas per farm differ between what we would derive from the database (average area organic: 40ha, conventional: 62.7 ha) and what is reported in D6.3 (one organic farm with 40ha and conventional farms with 35 ha or 55 ha on average – thus both considerably lower than reported for the conventional farms in the database); furthermore, yields reported in D6.3 are 46t/ha on average for conventional farms and 35t/ha for the organic farm, while in the database, all yields are below 40t/ha and yields are partly very low for silage maize – down to 3.5 t/ha. It is also not communicated what is grown on the other areas covered by the farm size area beyond the area reported in "plot size" – which latter we may assume to be the forage maize area.

sixth of the total area to each farm type.[3] To cover 1000 ha of total area, this then results in about 58 ha silage maize taken from production by each farm type F10, F13, F14, F15 or F16, and 87ha by farm type F16 or F25 (F16 and F25 have three times maize in a five year crop rotations, while all the others have two times maize in five years).

Yields for the different crops are taken from FAOSTAT (an average over the years 2018-2022; using the values for artificial meadows for grass-clover), for silage maize being largely equal to the average conventional yields reported in Deliverable D6.3 (Meier et al. 2024a).

Farm_ID	Organic	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Maize count	Grass count	Crop rotation score	Rank
F03	yes	Grass_clover	Grass_clover	Maize	Barley	Grass_clover	1	3	1	1
F18	no	Maize	Grass_clover	Maize	Grass_clover	Grass_clover	2	3	2	2
F26	no	Grass_clover	Potato	Maize	Grass_clover	Potato	1	2	3	3
F23	no	Barley	Grass_clover	Maize	Triticale	Grass_clover	1	2	3	4
F06	no	Barley	Grass_clover	Maize	Barley	Grass_clover	1	2	3	4
F04	no	Grass_clover	Grass_clover	Maize	Barley	Maize	2	2	4	5
F24	no	Maize	Grass_clover	Maize	Maize	Grass_clover	3	2	5	6
F19	no	Grass_clover	Barley	Maize	Wheat	Maize	2	1	6	7
F14	no	Barley	Grass_clover	Maize	Oat	Maize	2	1	6	7
F25	no	Maize	Grass_clover	Maize	Wheat	Maize	3	1	7	8
F16	no	Grass_clover	Maize	Maize	Wheat	Maize	3	1	7	9
F08	no	Wheat	Rape	Maize	Wheat	Rape	1	0	8	10
F02	no	Sorghum	Barley	Maize	Barley	Sorghum	1	0	8	10
F12	no	Grass_clover	Grass_clover	Maize	Maize	Grass_clover	2	3	2	11
F20	no	Maize	Grass_clover	Maize	Grass_clover	Barley	2	2	4	12
F27	no	Maize	Grass_clover	Maize	Grass_clover	Barley	2	2	4	12
F17	no	Grass_clover	Maize	Maize	Grass_clover	Maize	3	2	5	13
F15	no	Wheat	Maize	Maize	Grass_clover	Barley	2	1	6	14
F10	no	Maize	Triticale	Maize	Barley	Grass_clover	2	1	6	14
F13	no	Grass_clover	Barley	Maize	Wheat	Maize	2	1	6	15

Table 3: Case study farms in Slovenia used for defining the baseline (table 2 in Deliverable D6.3, Meier et al. 2024a)

2.2.2. Vineyards in France

The baseline is characterised by conventional vineyards, i.e. as realised by the five farms EF02, EF03, EF04, EF06 and EF07 in the case study in France (cf. the following Table 4 below from Deliverable D6.3 (i.e. Table 11 in Meier et al. 2024a)), with the relevant farms highlighted.

[3] Given the uncertainties mentioned in the previous footnote, we currently assign a seventh of the total area to each of these seven farms/fields, i.e. a seventh of the total area is each cropped according to the corresponding crop rotation of the respective farm.

For France, the baseline is calculated by allocating the total area to the management type represented by the farms listed in Table 4 in proportion to their farm size, or, for a simpler solution in equal distribution, i.e. a fifth of the area to each farm type.[4] Yields for the different farms are taken from the case study data as reported in table 12 in Deliverable D6.3 (Meier et al. 2024a), resulting in 5.2t/ha.[5] These yields are considerably lower than those reported in FAOSTAT, that are rather around 7 to 7.5t/ha.

Farm_ID	Organic	Treatment count	Fungicide count	F.AI count	F.AI count organic	Human Health Impacts (µDALY/ha)	Ecosystem Quality Impacts (PDF.m2.yr/ha)	Resource Use Impacts (MJ/ha)	Human Health Damage costs (EUR/ha)	Ecosystem Quality Damage Costs (EUR/ha)	Resource Use Damage Costs (EUR/ha)	Rank
EF10	Yes	15	7	6	6	7'396	409	60	547	57	0.26	1
EF09	Yes	20	8	5	5	9'654	533	78	714	75	0.33	2
EF16	Yes	16	3	3	3	10'256	562	82	759	79	0.35	3
EF08	Yes	16	8	4	4	10'641	584	86	787	82	0.37	4
EF02	No	15	16	15	3	13'123	835	121	971	117	0.52	5
EF07	No	9	11	6	3	13'385	850	124	990	119	0.53	6
EF06	No	11	16	16	3	17'372	1'149	167	1'286	161	0.72	7
EF03	No	16	12	12	5	18'071	1'210	176	1'337	169	0.75	8
EF04	No	10	9	10	4	18'618	1'248	181	1'378	175	0.78	9

Table 4: Case study farms in France used for defining the baseline (table 12 in Deliverable D6.3, Meier et al. 2024a)

2.2.3. Seed potatoes in The Netherlands

The baseline is characterised by conventional seed potato growing, i.e. as realised by the five farms F08, F13, F14, F15 and F16 in the case study in The Netherlands (cf. the following Table 5 below from Deliverable D6.3 (i.e. Table 24 in Meier et al. 2024a)), with the relevant farms highlighted.

[4] D6.3 reports total crop area and farm size while the latter is partly missing and partly considerably larger than the former; we thus need to check back, which area corresponds to the vineyards and what is cropped on the remaining areas. We thus currently assign a fifth of the total area to each of these five farms, i.e. a fifth of the total area is each managed according to the corresponding farm.

[5] Which, when processing into wine, results in 3900 l/ha on average. This corresponds a share of 75% for winemaking, which roughly corresponds to the values reported in FAOSTAT.

Farm	Farming system	Human Health Damage costs (EUR/ha)	Ecosystem Damage Costs (EUR/ha)	Resource damage costs (EUR/ha)	Human Health Impacts (µDALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Resources (MJ/ha)	Treatments count	Fungicide count	F.AI count	Rank
F12	IPM	237.49	25.30	0.11	3209.36	180.70	26.46	5	3	3	1
F16	Conventional	251.26	27.23	0.12	3395.34	194.46	28.35	11	4	5	2
F08	Conventional	449.26	41.57	0.19	6071.03	296.95	43.47	8	5	5	3
F11	IPM	545.24	61.28	0.27	7368.12	437.70	63.81	11	4	4	4
F13	Conventional	612.40	67.97	0.30	8275.63	485.48	70.79	10	3	4	5
F15	Conventional	679.66	82.58	0.37	9184.53	589.86	86.10	9	4	5	6
F10	IPM	755.60	86.47	0.39	10210.84	617.65	90.10	17	5	5	7
F14	Conventional	1227.11	140.27	0.63	16582.55	1001.93	146.20	16	6	7	8

Table 5: Case study farms in The Netherlands used for defining the baseline (table 24 in Deliverable D6.3, Meier et al. 2024a)

For The Netherlands, the baseline is calculated by allocating the total area to the crop rotations represented by the farms listed in Table 5 in proportion to their farm size (crop rotation data is in principle available in the SPRINT case study database (Mark et al. 2024a; see also the related paper Mark et al. 2024b) – however, for the farms identified above, this information is missing). We thus refer to the general information reported above from Deliverable D6.3 and assume 1:3 crop rotations with two of the following crops barley, wheat, sugar beet or onions for the crop rotations of these farms. For a first assumption, we allocate the crop rotation potato, wheat, onion to the farms F08, F13, F15 and F16, and potato, barley, sugar beet to farm F14 (because this shows highest sustainability impacts), cf. Table 6, thus allocating an area of 200ha seed potatoes and thus a total area of 600ha (as potatoes are 1 in 3 years) to each of these farms as illustrative management practice for these areas.

	Crop 1	Crop 2	Crop 3
F08	potatoes	wheat	onion
F13	potatoes	wheat	onion
F15	potatoes	wheat	onion
F16	potatoes	wheat	onion
F14	potato	barley	Sugar beet

Table 6: Crop rotations for the baseline in the Dutch case study.

Potato yields for the different farms are taken from the case study data as reported in this database as well (Mark et al. 2024a), providing 40 or 39t/ha and one missing value, which we replaced with 39.5t/ha. Yields for the other crops are taken from FAOSTAT (potato yields taken from the case study also largely correspond to FAOSTAT yields, which were about 5% higher).

2.3. Scenario Dimensions

This section describes the dimensions that are used to build the option spaces in the modelling. These dimensions have been identified in Deliverable D6.4 (Meier et al., 2024b) and further details can also be

found there. Here we recap part of the description and analysis from D6.4 (Meier et al., 2024b, partly also copying single sentences, etc.), focusing on the aspects of direct relevance for the modelling. We reordered the dimensions to first list those directly related to pesticide use reduction, followed by more systemic approaches where pesticide use reduction is a central element (agroecology and organic agriculture) and then describing one dimension that captures actions that affect the whole food system and not only production. Finally, a dimension capturing some of the impacts of climate change is addressed, i.e. a dimension not being directly linked to management decisions but rather to the context such management decisions are embedded in.

2.3.1. Robust varieties

Relevant for the scenarios 2.1, 2.2 (both vineyard cases), 3.1 and 3.2 (both seed potato cases).

Robust varieties are investigated in two contexts, vineyards and seed potatoes. In vineyards, a particular situation arises as this is a permanent culture and a waiting period of three years is commonly assumed before returning to production after replacing plants. This thus requires some adjustments of the yield expectations in the short run. Furthermore, the AOC production standards (AOC: controlled designation of origin; French: appellation d'origine controlée) limits the share of robust varieties to 5% of the vineyard, thus forcing farmers implementing higher shares to leave this scheme with corresponding potential disadvantages, such as e.g. financial losses. For vineyards, it is expected that growing robust varieties results in a strong decrease in the number of pesticides applied and in the number of treatment frequency. Costs for mechanisation and labour are expected to rather decrease and yields and yield stability are expected to rather increase. For potatoes, no change in yield is expected.

Most importantly, there is considerable concern about resistance breakdown in robust varieties. Thus, a general expectation is that those should not be grown on more than 20% of the area.

2.3.2. Low residue strategy

Relevant for the scenario 2.1 (vineyard case)

The 'low residue strategy' proposed here is very specific for vineyards, consisting of omitting synthetic pesticides after the flowering period, replacing them with biological alternatives. This strategy interacts with other dimensions, in particular with "rainfall intensity", as overly wet conditions hinder efficient implementation. Yields are expected to decrease only slightly, while yield stability may decrease. A reduction is expected both regarding the number of different synthetic fungicides used and the treatment frequency with synthetic fungicides. However, if the total number of fungicides (synthetic and non-synthetic) would increase, such decrease may not realise.

2.3.3. Agroecological measures

Relevant for the scenarios 1.1, 3.1 and 4.1

Agroecological measures are captured by farms replacing synthetic herbicides by implementing a wider/ more diverse crop rotation and/or by increasing mechanical weeding. Important parts in wider crop rotations are legumes and temporary grass, the latter being an effective measure to control perennial weeds. Grass is partly even grown in two consecutive years, e.g. in organic agriculture. For mechanical weeding, slight to strong yield decreases are expected. Doing only mechanical weeding, without any chemical treatments is seen as a big challenge with a high risk of considerably yield reductions. A combination of grass in wider crop rotations plus mechanical weeding is seen as very promising. Economic costs of both wider crop rotations and mechanical weeding can be high, as wider crop rotations come with high opportunity costs from foregone production of crops that give much incomes, such as seed potatoes, and mechanical weeding partly need investments in new machinery and require more labour.

Fore mechanical weeding, particular challenges arise when it interacts with heavy rainfalls and in very wet years. For example, the critical days before weeds overtake the maize can be missed, as it takes at least a few days without rain to hoe. In contrast, herbicide application remains a viable option even if it rains 5 hours after application.

Albeit not centrally named for vineyards (scenarios 2.1 and 2.2), INRAE (2023) offers some inspirational agroecological scenario consisting of 'mosaics of crops' – mixing vineyards, fruit trees, hazelnut trees, cereals, and pastures – and of semi-natural habitats, including hedgerows, copses, flowering strips, and wetlands. Together these create "complex and resilient landscapes, where pests and diseases are regulated" (INRAE, 2023, p. 7). This is one aspect how agroecological practices are covered in scenario 4.1. Generally, some further inspiration for systemic agroecological scenarios will be taken from this report INRAE (2023) for implementation in scenario 4.1. This is particularly adequate for the food-system level focus of SOLm.

2.3.4. Organic share

Relevant for the scenarios 1.2, 2.2, 3.2 and 4.1

The dimension 'organic share' represents a measure for system re-design to reach pesticide use reduction, which is well-embedded in a whole balanced agronomic production context for which in-field experience has been gained and practices have been improved since decades. Central to organic shares are changes in crop rotations, to account for the challenges that arise with not using synthetic pesticides and mineral fertilizers, a focus on healthy fertile soils where the use of manure and compost play an important role, and the dependence of functioning ecosystem dynamics and biodiversity for supporting biological plant protection.

For the crops in the case studies, organic agriculture is quite challenging, in particular for forage maize, and seed potatoes. Instead of forage maize, organic farms rather tend to grow grass for silage, complemented with wheat or barley as energy-rich feed components. Organic potato production faces increased labour requirements, lower yield stability and quality (from 90% good quality to 60-70%), and considerable yield decreases, in particular under wet conditions, compared to conventional production. Organic wine seems somewhat easier regarding keeping yields, as they are expected to decrease only slightly, and quality, which will not change. Treatment frequency rather increases, up to 40% but input costs will decrease.

2.3.5. Reduced feed-food competition

Relevant for the scenario 1.2

The dimension 'reduce the amount of silage maize (and other feed) produced on cropland' represents a gradual reduction of the food-competing-feed production and a consequent reduction in the number of animals to a final number that can still be fed with the remaining feed resources. These are permanent pastures (whose area is assumed to stay constant), forage from cropland, as required for good crop rotations based on agronomic reasons (e.g. temporary grasslands for weed control in organic systems, etc.), and residues and by-products from agriculture and processing (e.g. rapeseed cake). This is a most encompassing systemic dimension, not only addressing the production side but also the consumption, as it results in considerably changes in outputs from the areas and production systems (in particular much less animal source food products). The areas formerly cropped with forage maize and other food crops are freed for alternative use, such as cropping of food crops directly, or also assigning it to nature conservation areas or biodiversity support areas, etc.

2.3.6. Rainfall intensity

Relevant for the scenarios 1.1, 1.2, 2.1, 2.2, 3.1, 3.2, 4.1 (i.e. for all scenarios)

This dimension is of different character than the dimensions covered above, as it does not refer to a management change but rather to context variables that are not influenced by farmers' decisions but strongly influence what they can achieve and how the crops grow.

As written in Deliverable D6.4 (Meier et al., 2024b), the dimension 'rainfall intensity' relates to the observation that a reduction of synthetic pesticides makes farms more weather dependant and less flexible in their response to weeds: "Factors such as increased weather dependency, mainly in excessively wet conditions, contribute to a potentially serious yield loss. Particularly in very wet years, the critical days before weeds overtake the maize can be missed, as it takes at least a few days without rain to hoe. In contrast, herbicide application remains a viable option even if it rains 5 hours after application" (Meier et al., 2024). Thus, rain during critical weeding periods can delay or prevent mechanical weeding, leading to increased pest risks and reduced effectiveness in mitigating yield gaps.

More generally, this dimension captures some impacts of climate change and could in principle be expanded to also cover other aspects of climate change, such as prolonged warm periods that may foster earlier/more probable/stronger pest outbreaks, etc. thus also increasing the risk that pesticide reduction strategies result in larger yield losses if not complemented with specific measures to hedge against such climate risks.

Currently it is implemented in three levels of low, medium and high rainfall intensity, with "low" not affecting yields, while "medium" results in a moderate and "high" in a somewhat higher yield loss. If interacting with other dimensions, such as mechanical weeding, the yield loss can become large. For specific values used in the model, see Table 7.

2.3.7. Combined implementation of the scenario dimensions

After the description of each scenario dimension separately, we combine them according to the scenarios identified in Deliverable D6.4 (Meier et al., 2024b) and displayed in section 2.2, Table 1. For each of these scenarios, the relevant dimensions and the specific parameter choices related to those are displayed in Table 7 below, also indicating the characteristics of the crop rotations. Where possible, crop rotations were further specified inspired by farms in the case study sample, such as detailed in the case study specific sections further down (cf. section 2.3.7.1 ff). Generally, modelling the scenario dimensions of the pesticide reduction strategies is either done via changes in the crops grown (wider and more diverse crop rotations; organic crop rotations; replacing feed with food crops) or the yields of the crops grown (organic production; mechanical weeding; robust varieties; low residue strategy; rainfall intensity), summarised as follows for the seven different dimensions (agroecology counting as two), also indicating where specific interactions between dimensions arise (relevant for some dimensions in combination with rainfall intensity):

- Robust varieties — different yields and inputs
- Low residues — different yields and inputs, **interaction** with rainfall intensity
- Agroecology: wider crop rotations — different crops, in particular more grass
- Agroecology: mechanical weeding — different yields and inputs, **interaction** with rainfall intensity
- Organic shares — different crops, yields and inputs, **interaction** with rainfall intensity
- Reduced feed-food competition — different crops, in particular less silage maize
- Rainfall intensity — different yields

The yield reductions indicated below are formulated in relation to the baseline yields and are implemented in the model in a multiplicative way. See for example silage maize in scenario 1.2: the yield reduction of 20% from organic production, combined with the yield reduction from medium rainfall intensity in organic production of 10% results in a total yield reduction of 28% (derived in multiplicative

way as follows: organic yields = 100%-20%=80% or 0.8; yields with medium rainfall intensity = 100%-10%=90% or 0.9; yields under combined effects = 0.8*0.9 = 0.72 or 72%, i.e. a reduction of 28%.

In the following, after Table 7, the scenarios for each case study covered in this deliverable are described in detail, in particular providing information on the farms and their crop rotations that are used as a basis for the scenario calculations (cf. the general explanations on scenario implementation at the beginning of section 2.2). For further details, see also the separate excel-file "sprint_d6_5_croprotation_impact_scenario.xlsx".

Case	Scenario	Dimension 1	Dimension 2	Dimension 3
Silage maize (Slovenia)	1.1	Agroecological measures: implemented on 0,25,50,75 and 100% of the areas; - Wider and more diverse crop rotations with silage maize 2 times, grass-clover mixture 2 times, cereal once, legume crop once; cover crops in winter. Or, concrete from Deliverable D6.3 (Meier et al. 2024a): twice or three times grass-clover mixture instead of only once in five years - Mechanical weeding (5% lower maize yields; no herbicide inputs; 20% more labour input)	(none)	Rainfall intensity: Implemented at levels low, middle, high; - Maize yields reduced by 0%, 5% and 10%, if **interacting** with mechanical weeding, the values of 0%, 25% and 50% apply.
	1.2	Organic share: implemented on 0,25,50,75 and 100% of the areas; - Wider and more diverse crop rotations with silage maize once, grass-clover mixture 2 times, cereal once, food cereal once, legume food crop once and legume forage crop once; cover crops in winter; no use of synthetic and change to organic pesticides; no use of mineral fertilizers. Organic maize yields are 20% lower, organic cereal yields are 30% lower, organic legume yields are 10% lower, organic grass-clover and alfalfa yields are 10% lower, organic vegetable and oilseed yields are	Reduced feed-food competition: implemented on 0,25,50,75 and 100% of the areas; - Replacement of silage maize areas with food crops: silage maize zero times, grass-clover mixture once, cereal twice to three times, legume crops once or twice.	Rainfall intensity Implemented at levels low, middle, high; - Maize yields reduced by 0%, 5% and 10%, if **interacting** with organic production, the values of 0%, 10% and 20% apply.

		30% lower and organic potato yields are 25% lower.		
Vineyards (France)	2.1	Low residue strategy: implemented on 0,25,50,75 and 100% of vineyard areas; - Grape yields reduce by 5%; fungicide use drops by 75%	Robust varieties implemented on 0,25,50,75 and 100% of vineyard areas; - yields unchanged	Rainfall intensity Implemented at levels low, middle, high; Grape yields reduced by 0%, 2.5% and 5%, if **interacting** with low residue strategy, the values of 0%, 10% and 20% apply.
	2.2	Organic share: implemented on 0,25,50,75 and 100% of vineyard areas; - Grape yields reduce by 5%	Robust varieties implemented on 0,25,50,75 and 100% of vineyard areas; - yields unchanged	Rainfall intensity Implemented at levels low, middle, high; Grape yields reduce by 0%, 2.5% and 5%, if **interacting** with organic shares, the values of 0%, 5% and 10% apply.
Seed potatoes (The Netherlands)	3.1	Agroecological measures implemented on 0,25,50,75 and 100% of the areas; - Wider and more diverse crop rotations from 1:3 in the baseline to 1:5, with potatoes once, grass-clover mixture once, wheat or barley once, sugar beet or onion once, legume crop once. Other concrete suggestions from the case study (Deliverable D6.3, Meier et al. 2024a): potatoes-mustard-wheat-buckwheat, or potatoes-salad-carrots-cauliflower. - Mechanical weeding (5% lower potato yields; no herbicide inputs; 20% more labour input)	Robust varieties implemented on 0,25,50,75 and 100% of the areas; - yields unchanged	Rainfall intensity Implemented at levels low, middle, high; Potato yields reduce by 0%, 10% and 20%, if **interacting** with mechanical weed management, the values of 0%, 25% and 50% apply.
	3.2	Organic share:	Robust varieties	Rainfall intensity

		implemented on 0,25,50,75 and 100% of potato areas; - Wider and more diverse crop rotations with potatoes once, grass-clover mixture 1-2 times, complex choices of other crops including legumes, as detailed in the crop rotations of the organic farms in the case study; no use of synthetic and change to organic pesticides; no use of mineral fertilizers. Organic potato yields are 25% lower, organic cereal yields are 30% lower, organic legume yields are 10% lower, organic grass-clover and alfalfa yields are 10% lower, and organic vegetable and oilseed yields are 30% lower.	implemented on 0,25,50,75 and 100% of potato areas; - yields unchanged	Implemented at levels low, middle, high; Potato yields reduce by 0%, 10% and 20%, if **interacting** with organic shares, the values of 0%, 20% and 40% apply.
Agroecological and pesticide-reduced food systems in Europe	4.1	Organic share	Various aspects as detailed in INRAE 2023	Rainfall intensity

Table 7: Parameter choices for implementing the various scenarios in SOLm. Information on "reductions" and "increases", etc. (e.g. of yields) are always defined in relation to the baseline values (for the baselines, see Table 2)

Concretely, the implementation of the different levels for each dimension works via the corresponding share of areas cropped according to the farms available for this scenario (for details on which farms with which crop rotations are present for which scenarios, see the following subsections below). Thus, the corresponding share of the area of the key crop is managed accordingly – and all the other crop rotation elements as well. For cases, where two dimensions may or may not refer to the same areas, we generally implement this by first applying them to different areas, as much as possible, and only then starting to apply them on the same areas. Thus, for example, if robust varieties and agroecological practices are applied each to the level of 25%, then 25% of the area is managed agroecologically, 25% of the area is managed with robust varieties (and these are NOT the same areas), and thus 50% of the area are managed conventionally. If each of these dimensions is implemented to 75%, this means that 75% are managed agroecologically, 75% are managed with robust varieties, which means, that concretely 25% are managed with both these practices, 50% are managed solely agroecologically without robust varieties, and 50% are cropped with robust varieties but not managed agroecologically.

2.3.7.1. Scenario implementation for silage maize in Slovenia

In scenario 1.1, **wider crop rotations** are implemented (besides mechanical weeding). From the case study, a number of farms provide such. We chose the *conventional* farms with two or three times clover-grass and a crop rotation score of 1,2 or 3 as examples for implementation the scenario (i.e. farms F06, F12, F18, F23 and F26), cf. the farms highlighted in Table 8 below. This then also allows to use the corresponding impact indicators.

Farm_ID	Organic	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Maize count	Grass count	Crop rotation score	Rank
F03	yes	Grass_clover	Grass_clover	Maize	Barley	Grass_clover	1	3	1	1
F18	no	Maize	Grass_clover	Maize	Grass_clover	Grass_clover	2	3	2	2
F26	no	Grass_clover	Potato	Maize	Grass_clover	Potato	1	2	3	3
F23	no	Barley	Grass_clover	Maize	Triticale	Grass_clover	1	2	3	4
F06	no	Barley	Grass_clover	Maize	Barley	Grass_clover	1	2	3	4
F04	no	Grass_clover	Grass_clover	Maize	Barley	Maize	2	2	4	5
F24	no	Maize	Grass_clover	Maize	Maize	Grass_clover	3	2	5	6
F19	no	Grass_clover	Barley	Maize	Wheat	Maize	2	1	6	7
F14	no	Barley	Grass_clover	Maize	Oat	Maize	2	1	6	7
F25	no	Maize	Grass_clover	Maize	Wheat	Maize	3	1	7	8
F16	no	Grass_clover	Maize	Maize	Wheat	Maize	3	1	7	9
F08	no	Wheat	Rape	Maize	Wheat	Rape	1	0	8	10
F02	no	Sorghum	Barley	Maize	Barley	Sorghum	1	0	8	10
F12	no	Grass_clover	Grass_clover	Maize	Maize	Grass_clover	2	3	2	11
F20	no	Maize	Grass_clover	Maize	Grass_clover	Barley	2	2	4	12
F27	no	Maize	Grass_clover	Maize	Grass_clover	Barley	2	2	4	12
F17	no	Grass_clover	Maize	Maize	Grass_clover	Maize	3	2	5	13
F15	no	Wheat	Maize	Maize	Grass_clover	Barley	2	1	6	14
F10	no	Maize	Triticale	Maize	Barley	Grass_clover	2	1	6	14
F13	no	Grass_clover	Barley	Maize	Wheat	Maize	2	1	6	15

Table 8: Case study farms in Slovenia used for defining the wider crop rotations in the scenarios (table 2 in Deliverable D6.3, Meier et al. 2024a)

In scenario 1.2, **organic crop rotations** and crop rotations for **reduced feed-food-competition** are implemented. For this, only one organic sample farm is available (Farm F03)[6], thus not providing much basis for specifying the scenario assumptions in due detail. We thus choose a 1:6 crop rotation with silage maize once, grass-clover mixture 2 times, feed cereal once, food cereal once, legume food crop once and legume forage crop once; however, when consulting the database (Mark et al. 2024a), six of

[6] Pending the clarification mentioned above, regarding farm/field number and number of organic/conventional farms in this case study in Slovenia. However, cf. also the footnote to Table 2, clarifying the number of organic farms in the case study (6) and used for the calculations here (1).

the 12 farms in the Slovenian case study are labelled organic and provide information on crop rotations. We thus decided to take those as a basis for implementing the dimension "organic share", by allocating equal shares of the organic areas to these farm types each (farms F01, F03, F05, F07, F09 and F11)[7], here displayed in the following Table 9. We drop F09.1 and F09.2, however, as they do not include silage maize.

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
F01.1	alfalfa	triticale	maize	triticale	Maize
F01.2	alfalfa	alfalfa	maize	triticale	Alfalfa
F03.1	grass clover mix	grass clover mix	maize	Winter barley	grass clover mix
F03.2	grass clover mix	grass clover mix	maize	Winter barley	grass clover mix
~~F05.1~~	~~cannabis sativa~~	~~kamut~~	~~maize~~	~~Oat~~	~~Winter wheat~~
~~F05.2~~	~~millet~~	~~Cannabis sativa~~	~~maize~~	~~Oat~~	~~Winter wheat~~
F07.1	grass clover mix	grass clover mix	maize	Triticale	grass clover mix
F07.2	grass clover mix	grass clover mix	maize	Triticale	grass clover mix
~~F09.1~~	~~alfalfa~~	~~alfalfa~~	~~Winter barley~~	~~triticale~~	~~Alfalfa~~
~~F09.2~~	~~Winter barley~~	~~triticale~~	~~Winter barley~~	~~grass clover mix~~	~~grass clover mix~~
F11.1	grass clover mix	Winter wheat	maize	Winter wheat	grass clover mix
F11.2	grass clover mix	grass clover mix	maize	Winter wheat	Winter barley

Table 9: Crop rotations in the organic farms in the Slovenian case study according to the database Mark et al. (2024a) (F09 is dropped as it does not contain maize). Cannabis sativa being a very special crop without food or feed value, we drop the corresponding rotations from our calculations

For the reduced feed-food competition, the primary approach is to replace maize with a food cereal such as wheat or, depending on the other elements of the crop rotation, with a food pulse. For a first implementation, we thus take the baseline crop rotations as displayed in Table 3 and replace maize by wheat, barley, oats or pulses, as indicated in Table 10 below, partly choosing pulses twice, partly once but cereals three times; we assume that the crop rotation design is such that two components with pulses are chosen such as to ensure good growth. For pulses, we take soybeans and, if two pulses are included in the rotation, peas for dry kernels, as according to FAOSTAT, these report highest grain yields of all food pulses grown in Slovenia.

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
F19adj	grass clover mix	barley	pulses	wheat	pulses
F14adj	barley	grass clover mix	pulses	oat	wheat
F25adj	Barley	grass clover mix	pulses	wheat	pulses
F16adj	grass clover mix	barley	pulses	wheat	oat
F15adj	wheat	oat	pulses	grass clover mix	barley
F10adj	pulses	wheat	pulses	barley	grass clover mix
F13adj	grass clover mix	barley	pulses	wheat	oat

[7] It is not exactly clear, what the two entries per farm ID refer to, most likely two different fields. We thus take the full information from this data and implement all crop rotation options offered.

Table 10: Crop rotations for reduced feed-food competition, "adj" indicating from which case study crop rotation it has been derived.

For the combinations of organic crop rotations with reduced feed-food competition, we replace maize (and triticale) in the organic rotations with pulses or food cereals, and we also include the rotations from farms F09.1 and F09.2 as they do not contain maize:

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
F01.1adj	alfalfa	wheat	pulses	barley	Pulses
F01.2adj	alfalfa	alfalfa	Pulses	wheat	Alfalfa
F03.1adj	grass clover mix	grass clover mix	Pulses	Winter barley	grass clover mix
F03.2adj	grass clover mix	grass clover mix	pulses	Winter barley	grass clover mix
~~F05.1adj~~	~~cannabis sativa~~	~~kamut~~	~~maize~~	~~Oat~~	~~Winter wheat~~
~~F05.2adj~~	~~millet~~	~~Cannabis sativa~~	~~Maize~~	~~Oat~~	~~Winter wheat~~
F07.1adj	grass clover mix	grass clover mix	Pulses	wheat	grass clover mix
F07.2adj	grass clover mix	grass clover mix	pulses	Wheat	grass clover mix
F09.1	alfalfa	alfalfa	Winter barley	pulses	Alfalfa
F09.2	Winter barley	pulses	Winter barley	grass clover mix	grass clover mix
F11.1adj	grass clover mix	Winter wheat	Pulses	Winter wheat	grass clover mix
F11.2adj	grass clover mix	grass clover mix	pulses	Winter wheat	Winter barley

Table 11: Crop rotations in the organic farms with reduced feed-food competition, "adj" indicating from which case study crop rotation it has been derived. Cannabis sativa being a very special crop without food or feed value, we drop the corresponding rotations from our calculations.

2.3.7.2. Scenario implementation for vineyards in France

Vineyards being permanent cropping systems, no change in crop rotations but only changes in yields are modelled in the scenarios 2.1 and 2.2. Hence no further details beyond the assumptions on yields as displayed in Table 7 need to be provided here. As a basis for the impact assessment for the conversion to organic agriculture (scenario 2.2), we utilize the organic farms covered in the case study. For completeness, we display them in the following Table 12.

Farm_ID	Organic	Treatment count	Fungicide count	F.AI count	F.AI count organic	Human Health Impacts (µDALY/ha)	Ecosystem Quality Impacts (PDF.m2.yr/ha)	Resource Use Impacts (MJ/ha)	Human Health Damage costs (EUR/ha)	Ecosystem Quality Damage Costs (EUR/ha)	Resource Use Damage Costs (EUR/ha)	Rank
EF10	Yes	15	7	6	6	7'396	409	60	547	57	0.26	1
EF09	Yes	20	8	5	5	9'654	533	78	714	75	0.33	2
EF16	Yes	16	3	3	3	10'256	562	82	759	79	0.35	3
EF08	Yes	16	8	4	4	10'641	584	86	787	82	0.37	4
EF02	No	15	16	15	3	13'123	835	121	971	117	0.52	5
EF07	No	9	11	6	3	13'385	850	124	990	119	0.53	6
EF06	No	11	16	16	3	17'372	1'149	167	1'286	161	0.72	7
EF03	No	16	12	12	5	18'071	1'210	176	1'337	169	0.75	8
EF04	No	10	9	10	4	18'618	1'248	181	1'378	175	0.78	9

Table 12: Case study farms in France used for specifying the scenario 2.2 with increasing organic shares (table 12 in Deliverable D6.3, Meier et al. 2024a)

2.3.7.3. Scenario implementation for seed potatoes in The Netherlands

The wider crop rotations implemented in scenario 3.1 are specified as follows in Table 13 (cf. also Table 7). The yields for the additional crops were taken from FAOSTAT, based on an average over the years 2018-2022, using the values for artificial meadows for grass-clover.

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
Farm1	potato	grass clover mix	wheat	Sugar beet	Pulses
Farm2	potato	grass clover mix	barley	onion	Pulses
Farm3	potato	mustard	wheat	buckwheat	
Farm4	Potato	salad[8]	carrots	cauliflower	

Table 13: Wider crop rotations for the reduced pesticide use seed potato production scenarios in the Dutch case study.

For the organic crop rotations used in scenario 3.2, we refer to the data on the organic farms provided in the database (Mark et al. 2024a). These are displayed in the following Table 14. Some rotations are missing, we thus disregard these farms; others seem somewhat too simplistic without grass clover, so we decided to add such; and one seems very complex (F06), so we simplified considerably.

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6
F01	grass clover mix	cauliflower	potato	Grass clover mix	Celeriac[7]	pumpkin
F02	carrot	potato	Beans[7]	onion	Pulses	Grass clover mix
F03	potato	mustard	wheat	buckwheat	Grass clover mix	Grass clover mix
~~F04~~						
~~F05~~						

[8] «Celeriac» is modelled as «other vegetables» and «beans» as «other beans, green".

F06	onion	carrot	potato	mustard	spelt	Grass clover mix
~~F07~~						

Table 14: Organic crop rotations for the reduced pesticide use seed potato production scenarios in the Dutch case study. The information is missing for farms F04, F05 and F07, hence these are not included.

2.4. Indicators

Indicators used to assess the baseline and the various scenarios are as follows:

- The output from the whole agricultural area considered is calculated as **harvested yield** from the various crops and grasslands (in total fresh matter production).
- Impacts are assessed by using the per-hectare values for
    - **human health**,
    - **ecosystem quality** and
    - **resource use** impacts as described and reported in Deliverable D6.1 (Fantke et al. 2023), as well as the
    - aggregated **monetary sustainability costs** related to this, as also provided in Deliverable D6.1 (Fantke et al. 2023).

  Thus, for detailed description of these indicators, please refer to Deliverable D6.1 (Fantke et al. 2023). Data on these impacts is available for the key crops (forage maize in Slovenia, vineyards in France and seed potatoes in The Netherlands) only, and the corresponding impacts from the other elements in the crop rotation are thus not calculated and missing. This biases the results, as a reduction in key crop areas directly results in a reduction in impacts, while corresponding additional impacts from increasing other areas are not accounted for. For a thorough and non-biased assessment of the sustainability impacts of the various scenarios, it is necessary to also cover the impacts from the other crops.

- Furthermore, impact on food and feed provision are derived from the harvested yields in the form of
    - **food calories, protein and fat** provided (for food crops), as well as
    - **gross feed energy** (for feed crops). The latter is a proxy for **livestock units** that could be fed by this to relate it to potential consequences of a scenario on livestock numbers, as well as to corresponding changes in **milk and meat** production.

Trade is not assessed explicitly, but a potential difference in food and feed provision between a scenario and the baseline could be interpreted as the requirement for trade from abroad – or from other regions within the country.

Finally, some few numbers on **machinery costs** and **labour input** are available, that allow for some gross comparisons for certain scenarios in Slovenia and France. Given the scarce data, this is not calculated within full model runs but simply by providing and comparing averages.

The specific numbers used for the sustainability impacts (the three impact categories plus the monetary aggregate) on farm level are collected in the separate excel-file "sprint_d6_5_croprotation_impact_scenario.xlsx". The parameters for the other indicators are taken from SOLm.

3. Results

In the following, some key results from the model runs are presented. Further results are available in the excel sprint_d6_5_croprotation_impact_scenario.xlsx in the sheets result_1 and result2.

3.1. Silage maize in Slovenia

Figure 4 and Table 15 display the sustainability damage cost changes in the various scenarios in Slovenia. The figure shows the consequences of agroecological crop rotations, while the impact of mechanical weeding is not yet captured, as the quantitative values for the corresponding herbicide reduction are not readily available.

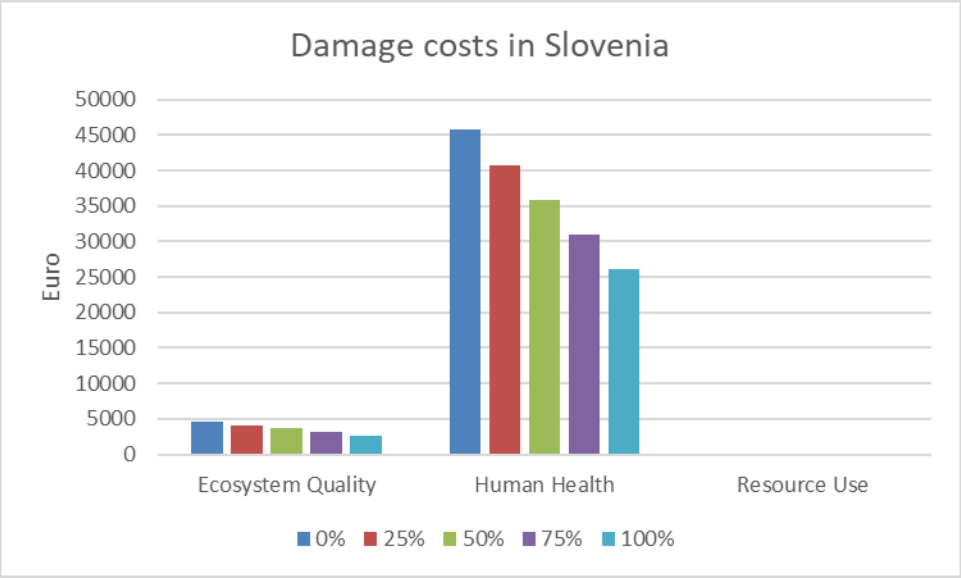

Figure 4: Sustainability impact related damage costs in the case study in Slovenia, for increased shares in agroecological practices (different colours: percentage of area under wider crop rotations). Resource use damage costs are negligible in relation to the other damage costs.

The option space illustrates the impact of organic production and reduced food-feed competition and combined strategies. Due to lack of data, the results are driven by the corresponding reduction in conventional forage maize areas for increasing organic shares, while the organic ones areas come without costs, and by the reduction of forage maize altogether in the scenarios with this focus.

			organic share				
food-feed competition reduction			0	25	50	75	100
		0	1	0.75	0.5	0.25	0
		25	0.75	0.5625	0.375	0.1875	0
		50	0.5	0.375	0.25	0.125	0
		75	0.25	0.1875	0.125	0.0625	0
		100	0	0	0	0	0

Table 15: Option space for the relative damage costs of increased organic production and reduced food-feed competition in the Slovenian case study.

Table 16 and Table 17 show the option space for feed and food production for scenarios with increased organic production and reduced feed-food competition, as well as combined with impacts from heavy rainfall. As the latter is impacting the key crop (forage maize) only, this has no effects on food provision. The general pattern is a decrease in feed production with reduced feed-food competition. Increased

organic shares result in reduced feed production for high feed-food competition, as the yield of feed crops are lower in organic production. For reduced feed-food competition, feed production is low and the impact of lower organic yields is also lower, wile the increased share of feed crops in organic crop rotations counteracts this trend, thus resulting in higher feed provision for higher shares of organic with low feed-food competition. Food provision reduces considerably with increased organic agriculture, due to lower yields and higher share of food crops (grass-clover) in organic crop rotations. This is then counteracted by reduced feed-food competition and suitable combinations of these strategies allow to provide the same amount of food calories while realising the benefits regarding pesticide impacts from these strategies.

		organic share				
reduced food-feed comp						
rainfall int.		0	25	50	75	100
0	0	1.00	0.91	0.82	0.74	0.65
0	25	0.79	0.73	0.67	0.61	0.55
0	50	0.58	0.55	0.52	0.49	0.46
0	75	0.37	0.37	0.37	0.37	0.37
0	100	0.16	0.19	0.21	0.24	0.27
50	0	0.96	0.87	0.78	0.70	0.61
50	25	0.76	0.70	0.64	0.58	0.53
50	50	0.56	0.53	0.50	0.47	0.44
50	75	0.36	0.36	0.36	0.36	0.36
50	100	0.16	0.19	0.21	0.24	0.27
100	0	0.92	0.82	0.74	0.65	0.58
100	25	0.73	0.66	0.61	0.55	0.50
100	50	0.54	0.50	0.48	0.45	0.43
100	75	0.35	0.35	0.35	0.35	0.35
100	100	0.16	0.19	0.21	0.24	0.27

Table 16: Option space for the feed production (gross feed energy supply) of increased organic production and reduced food-feed competition in the Slovenian case study.

		organic share				
reduced food-feed comp						
rainfall int.		0	25	50	75	100
0	0	1.00	0.84	0.67	0.51	0.35
0	25	1.29	1.10	0.91	0.72	0.53
0	50	1.58	1.37	1.15	0.93	0.72
0	75	1.87	1.63	1.39	1.14	0.90
0	100	2.16	1.89	1.62	1.35	1.08
50	0	1.00	0.84	0.67	0.51	0.35
50	25	1.29	1.10	0.91	0.72	0.53
50	50	1.58	1.37	1.15	0.93	0.72
50	75	1.87	1.63	1.39	1.14	0.90
50	100	2.16	1.89	1.62	1.35	1.08
100	0	1.00	0.84	0.67	0.51	0.35
100	25	1.29	1.10	0.91	0.72	0.53
100	50	1.58	1.37	1.15	0.93	0.72
100	75	1.87	1.63	1.39	1.14	0.90
100	100	2.16	1.89	1.62	1.35	1.08

Table 17: Option space for the food production (food calorie supply) of increased organic production and reduced food-feed competition in the Slovenian case study.

We finally report some data on machinery costs, as much as available in the database Mark (2024a). There, machinery use on silage maize for a number of baseline farms as well as farms corresponding to the wider crop rotations can be identified, resulting in average machinery costs for silage maize of Euro 270.-/ha for the baseline and Euro 420.-/ha for wider crop rotation, i.e. 55% higher.

3.2. Vineyards in France

The case study in France is focusing on a permanent crop, grapevine for wine production. Thus, crop rotations do not play a role and the impacts of the various scenarios are reflected via changes in yields. Primarily this is driven by a switch to organic production, as displayed in Figure 5 and Figure 6 below in the scenarios starting with "2_2". The three subsequent numbers refer to the share of agroecological practices, the share of organic agriculture and the share of food-competing feed reduction. In France, only the middle strategy (organic production) is relevant for the scenarios.

The pattern is exactly the same for all indicators, as these are based on average per area numbers times the areas cropped under conventional or organic management, thus scaling identically.

In addition, scenarios cover impacts of the use of reduced residue pesticide applications, robust varieties and rainfall intensity; Robust varieties result in reduced chemical plant protection application, but quantitative numbers on this are missing in the case study. For the reduced residue strategy, a reduction of 75% of fungicide application is expected. Given the aggregate farm-level impact numbers used here, we did not yet recalculate impacts to account for the consequences of fungicide reduction. Bot these strategies will result in some further impact reduction in addition of the 50% impact reduction that is possible with organic agriculture. For the case study, it is assumed that organic agriculture leads to a 5% yield reduction, thus showing marginal costs in productivity only in relation to the large gains in pesticide reduction.

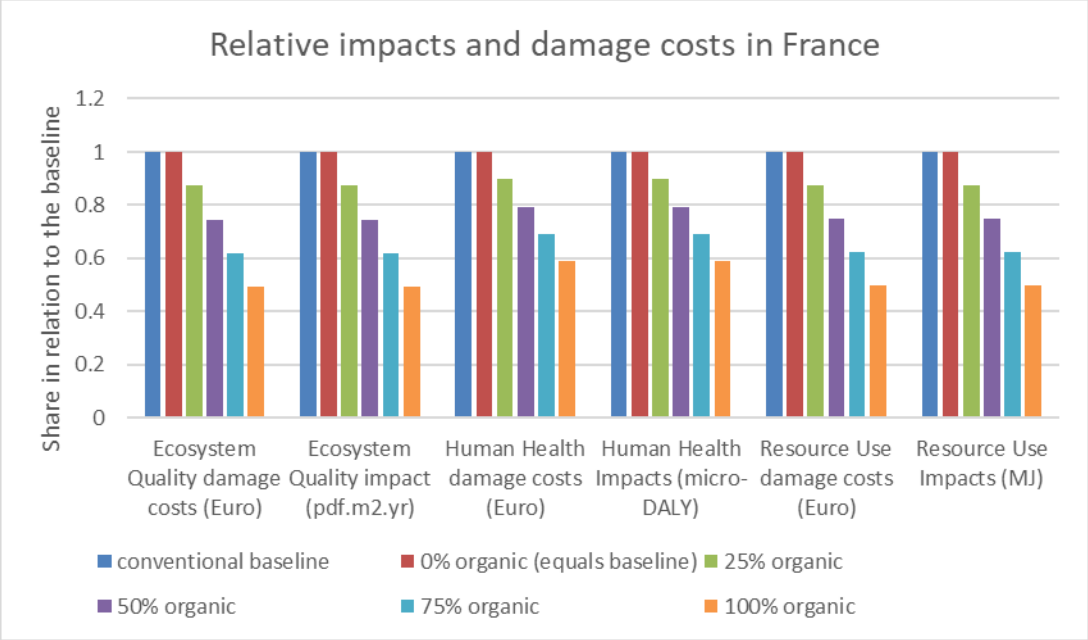

Figure 5: Sustainability impacts and related damage costs in the case study in France, relative values as shares in relation to the baseline. Scenarios cover increasing shares of organic production.

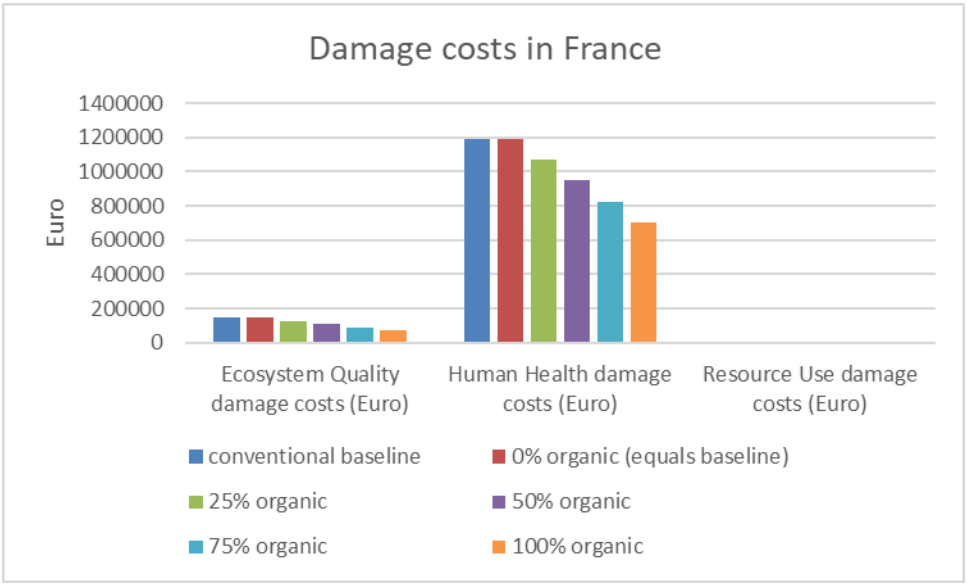

Figure 6: Sustainability damage costs in the case study in France, absolute values in Euros. Scenarios cover increasing shares of organic production. Resource use damage costs are negligible in relation to the other damage costs.

Table 18 below displays the option space for scenario 2_1, i.e. conventional production as a baseline, combined with low residue strategy, which results in some minor yield reduction, and robust varieties (that come with equal yields), further combined with the impacts of heavy rainfalls, that can have considerably yield impacts in combination with low residue strategies, in the extreme resulting in almost 25% yield losses.

		low residue				
rainfall int.	robust var.	0	25	50	75	100
0	0	1.00	0.99	0.98	0.96	0.95
0	25	1.00	0.99	0.98	0.96	0.95
0	50	1.00	0.99	0.98	0.96	0.95
0	75	1.00	0.99	0.98	0.96	0.95
0	100	1.00	0.99	0.98	0.96	0.95
50	0	0.98	0.94	0.91	0.88	0.86
50	25	0.98	0.94	0.91	0.88	0.86
50	50	0.98	0.94	0.91	0.88	0.86
50	75	0.98	0.94	0.91	0.88	0.86
50	100	0.98	0.94	0.91	0.88	0.86
100	0	0.95	0.90	0.85	0.81	0.76
100	25	0.95	0.90	0.85	0.81	0.76
100	50	0.95	0.90	0.85	0.81	0.76
100	75	0.95	0.90	0.85	0.81	0.76
100	100	0.95	0.90	0.85	0.81	0.76

Table 18: Option space for the relative production change of using robust varieties and low residue strategies in the case study in France, combined with the impacts of heavy rainfalls.

In the case study in France, machinery and labour costs was reported for the conventional baseline farms as well as for the organic farms (Mark 2024a). Analysing the average costs results in Euro 800.-/ha and Euro 2570.-/ha for machinery and labour costs, respectively, on conventional farms, and Euro 1020.-/ha and Euro 3040.-/ha for these costs on organic farms, i.e. 20-25% higher costs per ha.

3.3. Seed potatoes in the Netherlands

Figure 7 display the change in damage costs with the agroecological and organic strategies implemented in the Netherlands. Due to lack of data, implementation of the changes in damage costs was identical for the two cases, basically assigning zero costs to both agroecological and organic measures, thus resulting in this pattern of linear decrease to zero costs with increasing shares of agroecological or organic production.

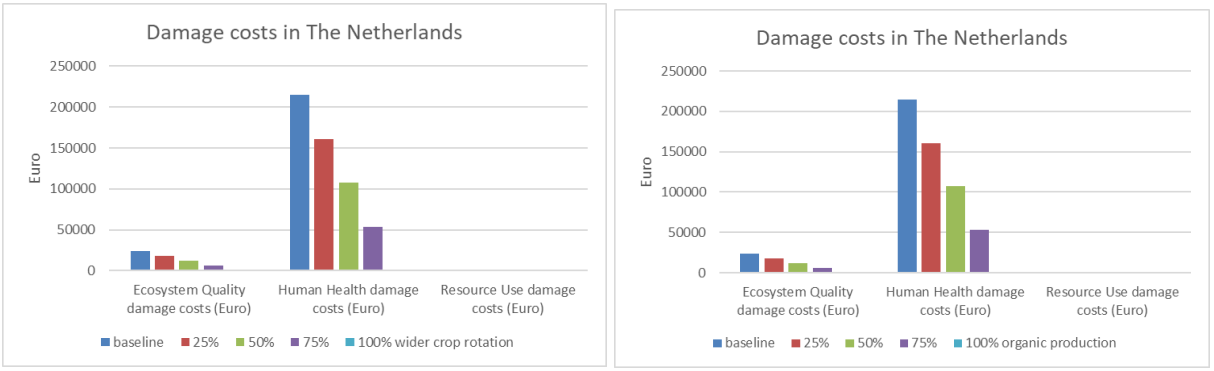

Figure 7: Sustainability damage costs in the case study in the Netherlands, absolute values in Euros. To the left: increased shares of areas managed with wider crop rotations (different colours indicating the different percentages of areas). To the right: increased shares of areas managed organically. Resource damage costs are negligible in relation to the other damage costs.

Production changes drastically with the agroecological and organic scenarios, cf. Figure 8. This is owed to the fact that grass and forage elements in the crop rotations increase considerably, thus resulting in trade-offs between pesticide reduction and food supply, based on changed crop rotations. The change are particularly large for organic production, where the larger yield reduction and stronger change in crop rotation elements towards food crops add to the reduction in food supply down to a third.

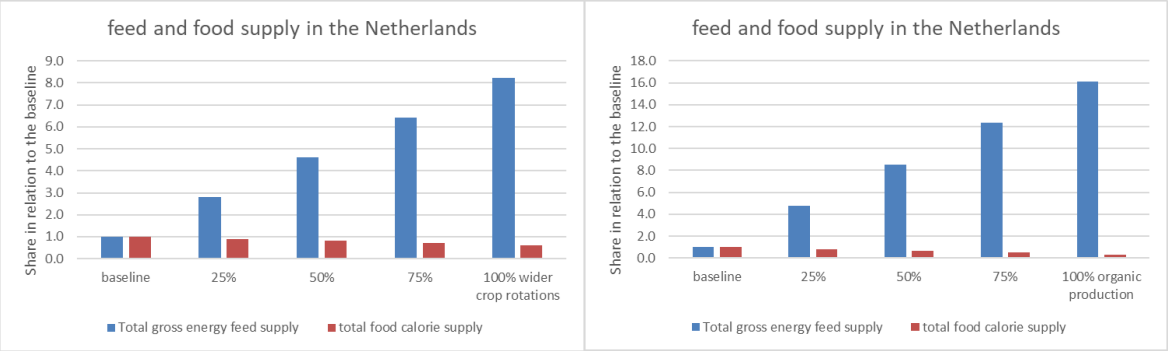

Figure 8: Production changes in the case study in the Netherlands, relative values for feed gross energy and food calorie supply in relation to the baseline, for increased shares of agroecological practices (wider crop rotations, to the left) and organic management (to the right).

4. Discussion and conclusions

The results indicate that pesticide reduction strategies come with considerable reductions in damage costs for human health, ecosystems and regarding resource use, while they also tend to lead to reduced production. Combined with other strategies, such as reduced feed production from croplands, these reductions in food supply can be counteracted and viable scenarios with lower pesticide use and the same or even increasing food supply are possible.

Generally, due action is needed to avoid the worst impact of interaction of climate change with pesticide reduction strategies, as captured by the impacts from heavy rainfall, that can drastically reduce yields. Thus, particular action should be taken to hedge against these adverse impacts.

The modelling assumed 1000 ha area for each scenario, managing it according to the crop rotations present in the farms of the case studies or, if such are not available, as identified and suggested in D6.4. The code of the model is written such that adjustment to these areas and farms can be undertaken relatively easy, if further questions need to be answered or if assumptions on which area is cropped with which crop rotation should be changed. Most importantly, damage costs are only reported for the key crops in the case studies, thus not providing full coverage of sustainability impacts from plant protection active substances application on all crops. This leads to biased results and for a comprehensive picture, damage costs of the other crops should be included as well.

Production of animal source food was captured via the proxy of feed energy supplied in the scenario, to better capture relative changes in this, not depending on specific assumptions on animal herds, milk and meat yields and livestock types managed with this feed. Besides grass-clover and specific feed crops, by-products only used as feed from processing the food products from the areas in the scenarios are included in the feed supply as well (thereby soybeans and grains are fully assigned to food use to better capture the full food production potential, albeit barley grains, for example, are to a large extent used for feed; triticale is allocated to feed).

In the scenarios, we largely used the assumptions on various processing paths of products as provided by FAOSTAT data, thus assuming a food system structure as present today (besides the allocation of soy

and grains to food, as mentioned above). This means, the food calories are derived not only from primary products such as wheat grains, but from the products as produced along the commodity treed, i.e. from wheat flour, distilled beverages, etc. – as currently observed in the case study countries. This then results in a certain supply of by-products that are used for feed (e.g. sugar beet pulp).

Finally, we mention that the full food system scenario inspired by the pesticide-free Europe scenarios from INRAE and the scenarios from TYFA has not yet been implemented.

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