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Research article

Extending shared socio-economic pathways for pesticide use in Europe: Pest-Agri-SSPs

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ABSTRACT

While pesticides are essential to agriculture and food systems to sustain current production levels, they also lead to significant environmental impacts. The use of pesticides is constantly increasing globally, driven mainly by a further intensification of agriculture, despite stricter regulations and higher pesticide effectiveness. To further the understanding of future pesticide use and make informed farm-to-policy decisions, we developed Pesticide Agricultural Shared Socio-economic Pathways (Pest-AgriSSPs) in six steps. The Pest-Agri-SSPs are developed based on an extensive literature review and expert feedback approach considering significant climate and socio-economic drivers from farm to continental scale in combination with multiple actors impacting them. In literature, pesticide use is associated with farmer behaviour and practices, pest damage, technique and efficiency of pesticide application, agricultural policy and agriculture demand and production. Here, we developed PestAgri-SSPs upon this understanding of pesticide use drivers and relating them to possible agriculture development as described by the Shared Socio-economic Pathways for European agriculture and food systems (Eur-Agri-SSPs). The Pest-AgriSSPs are developed to explore European pesticide use in five scenarios representing low to high challenges to mitigation and adaptation up to 2050. The most sustainable scenario (Pest-Agri-SSP1) shows a decrease in pesticide use owing to sustainable agricultural practices, technological advances and better implementation of agricultural policies. On the contrary, the Pest-Agri-SSP3 and Pest-Agri-SSP4 show a higher increase in pesticide use resulting from higher challenges from pest pressure, resource depletion and relaxed agricultural policies. Pest-Agri-SSP2 presents a stabilised pesticide use resulting from stricter policies and slow transitions by farmers to sustainable agricultural practices. At the same time, pest pressure, climate change and food demand pose serious challenges. Pest-Agri-SSP5 shows a decrease in pesticide use for most drivers, influenced mainly by rapid technological development and sustainable agricultural practices. However, Pest-Agri-SSP5 also presents a relatively low rise in pesticide use driven by agricultural demand, production, and climate change. Our results highlight the need for a holistic approach to tackle pesticide use, considering the identified drivers and future developments. The storylines and qualitative assessment provide a platform to make quantitative assumptions for numerical modelling and evaluating policy targets.

1. Introduction

Since their large-scale adoption in the mid-20th century, pesticides have become one of the world's most widely utilised chemical groups. In general, "pesticide" refers to a wide variety of substances, including herbicides, insecticides, fungicides, rodenticides, plant growth regulators, and other substances (*FAOSTAT*, 2022). An extensive amount of pesticides is used to produce crops (RaheliNamin et al., 2016). Pesticides help to control pests and weeds in all areas of agriculture, including horticultural, ornamental, cereal and vegetable crops (Ghimire and Woodward, 2013). Benefits of pesticide use include higher yields, reduced labour costs and lower fertiliser use (Dasgupta et al., 2001). Even with high pesticide use, globally, up to 40% of crop production is lost to pests annually (Savary et al., 2019; *FAO*, 2021). Hence, pesticide

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use helps to meet food security and the rising demand for feed, fibre, biofuel and other bio-based commodities (Popp et al., 2013). By 2050, pesticide use and related emissions are projected to intensify by 8–20% with increasing cropland area (Nagesh et al., 2022). The usage patterns of pesticides can widely vary across regions with different crop types, climatic conditions and consumer needs (Popp et al., 2013). However, high pesticide use poses significant health and environmental concerns (Sharma et al., 2019; Silva et al., 2019).

There is a constant increase in the use of pesticides globally, driven mainly by a further intensification of agriculture, despite tighter regulations and higher pesticide effectiveness (Chaplain et al., 2011). Several factors directly or indirectly influence the use of pesticides, including pest pressure (Bebber et al., 2014), rising production levels (Hu, 2020), increasing pesticide use intensity (Delcour et al., 2015; Möhring et al., 2020), policy regulations (Barzman and Dachbrodt-Saaydeh, 2011; Falkner et al., 2021; Handford et al., 2015; Hu, 2020; Kristoffersen et al., 2008; Lefebvre et al., 2015; Matousek et al., 2022; Silva et al., 2022), the costs and benefits of pesticide use (Bourguet and Guillemaud, 2016; Cooper and Dobson, 2007; Hedlund et al., 2020; Popp, 2011) and changes in crops grown and agricultural practices (Brückler et al., 2017; Peerzada et al., 2019; Hader et al., 2022). Climate change can also influence pesticide use by affecting agriculture in many ways (Bloomfield et al., 2006; Delcour et al., 2015; Genova Koleva, 2010; Kattwinkel et al., 2011; Patterson et al., 1999; Vernier et al., 2016), for instance, by influencing pest occurrence and abundance by affecting their development, reproduction, distribution, migration, and adaptation (Falkner et al., 2019; Porter et al., 1991). At the same time, the growing appreciation for sustainable agriculture and rising standards for human health and the environment suggest a future decline in pesticide use. In other words, multiple factors must be considered to understand the future dynamics of pesticide use. Although there is extensive peer-reviewed literature on the environmental impacts of pesticide use, only a few studies have investigated the dynamics of pesticide use and their connection with drivers such as climate (Bebber et al., 2013; Bloomfield et al., 2006; Delcour et al., 2015; Genova Koleva, 2010; Porter et al., 1991) and socio-economic change (Bourguet and Guillemaud, 2016; Hu, 2020; Kaczala and Blum, 2016; Popp et al., 2013; Wyckhuys et al., 2019). Current studies often disregard the influence of the various interacting drivers of pesticide use (Wyckhuys et al., 2022) at multiple scales, ranging from the farm to the continental scale. Approaches considering single drivers are primarily ineffective in informing policy development (Alexandratos and Bruinsma, 2012; Hu, 2020; Mateo-Sagasta et al., 2017) and should essentially reflect on drivers of global change corresponding to both increase and decrease in pesticide use (Hader et al., 2022). Hence, to improve the understanding of pesticide use and fill the existing knowledge gaps, a dynamic sense of the relevant social, economic, technological, political and climate drivers of agriculture and pesticide use is needed.

For other environmental issues, a variety of scenarios has been developed in Global and Regional Environmental Assessments to explore alternative futures (Cosgrove and Rijsberman, 2000; Maury et al., 2017; Mitter et al., 2020; Mora et al., 2020; O'Neill et al., 2015; Raskin, 2004; Watson et al., 2001). Such scenarios describe plausible and internally consistent views of the future. They provide an interdisciplinary framework for analysing and evaluating solutions for complex environmental problems (Alcamo, 2008). In this article, we use a scenario approach to improve the insights into the dynamics of pesticide use under future climate and socio-economic change. Pesticide use widely varies around the globe due to differences in climate, policy, regulations and agricultural management, making it challenging to track the dynamics all at once. Hence, we explore future European pesticide use by providing alternative scenarios. The Shared Socio-economic Pathways for European Agriculture and food systems (Eur-Agri-SSPs) provide five storylines (i.e. qualitative scenarios) (Mitter et al., 2020) and were developed following a detailed and stakeholder-inclusive protocol (Mitter et al., 2019). They offer a welcome platform for considering the future of European pesticide use. The Eur-Agri-SSPs outline plausible future developments for European agriculture and food systems considering challenges to climate change mitigation and adaptation until 2050 (Mitter et al., 2020). However, this set of scenarios lacks essential drivers to consider the future European pesticide use. To elaborate on the existing storylines and integrate the dynamics of pesticide use, we first identify the main drivers of pesticide use across geographical scales. Second, develop a dynamic system diagram for the drivers, also addressing the drivers already part of the Eur-Agri-SSPs. Third, we extend the Eur-Agri-SSPs and include changes in pesticide use.

2. Methodology to develop scenarios for pesticide use

We present six steps for developing pesticide use scenarios for Europe (Fig. 1). The steps follow established scenario development protocols which have been applied for the Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2015), the Oceanic System Pathways (OSPs) (Maury et al., 2017) and the Eur-Agri-SSPs (Mitter et al., 2019). The scenarios are developed by combining a literature review, expert feedback and existing storylines of the Eur-Agri-SSPs and the SSPs. The steps in Fig. 1 are shown linearly for convenience, but some steps are iterative in practice.

Step 1. Establish the focal issue

The focal issue for the current research is to develop plausible future scenarios of pesticide use in Europe, whereby Europe is synonymously used for European Economic Area countries and the United Kingdom. We refer to the agricultural use of pesticides, including herbicides, insecticides, fungicides, nematicides and plant growth regulators. We focus on Europe for two reasons. First, the pesticide policies are approved with uniform EU regulations and directives despite heterogeneity in policies between the countries. Second, the Eur-Agri-SSPs provide a robust foundation for understanding plausible future changes in the European agriculture and food systems and are useful for developing pesticide use scenarios.

Step 2. Identify the drivers

A literature review was conducted to identify the most relevant drivers of pesticide use in Europe. Peer-reviewed articles were identified with the two web search engines SCOPUS and Web of Science with varying search word combinations for pesticide use, socio-economic factors or drivers, social, economic, political, regulation, and climate change. The search was limited to articles in environment, agriculture and biodiversity journals resulting in 389 peer-reviewed articles. The abstracts and content of these peer-reviewed articles were checked to select only studies with explicit reference to drivers of pesticide use. The articles referring to pesticide use in different forms, such as herbicides, insecticides, fungicides, nematicides and plant growth regulators, were also included. Additionally, we collected relevant articles and policy reports from the references of the previously identified literature. Based on these steps, 97 peer-reviewed articles were chosen and reviewed to identify the drivers of pesticide use on farm, country and continental scales. Additionally, the status quo of the driver and their influence on pesticide use and future development were documented in a database.

Step 3. Develop a system diagram

The drivers identified in the previous step were classified into direct and indirect drivers. A direct driver is defined as having a direct influence on pesticide use. For example, pesticide use is influenced by the rate and frequency of pesticide application. An indirect driver is any driver influencing a direct driver of pesticide use. For example, demand for agricultural commodities does not directly affect pesticide use. However, it drives agricultural production by targeting crop yield and pesticide application. After identifying the direct and indirect drivers on the farm, country and continental scales, their interactions were visualised in a system diagram. Where possible, the drivers are classified along the SSP thematic groups: economy & lifestyle, policy &

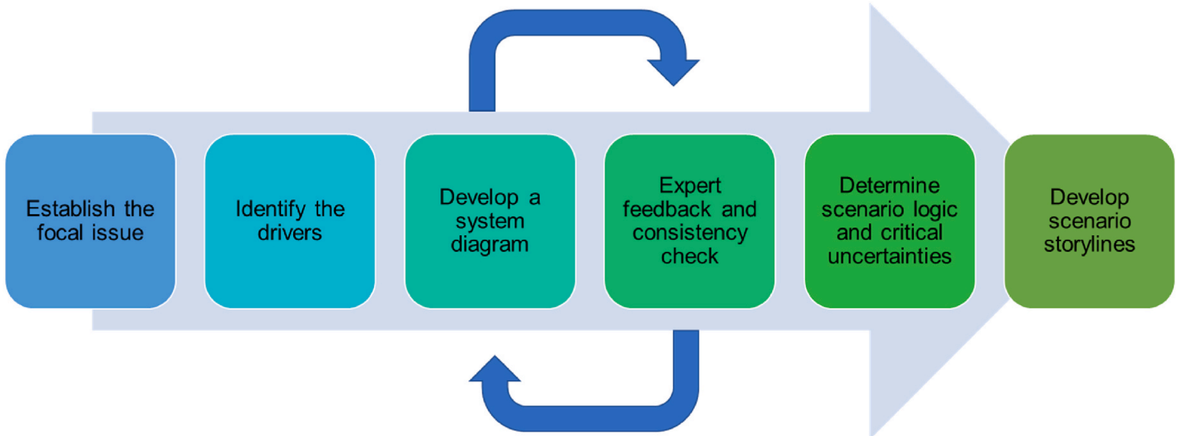

Fig. 1. Scheme representing the six steps to develop scenarios for pesticide use (based on Alcamo, 2008; Mitter et al., 2019).

institutions, technology and environment & natural resources (O'Neill et al., 2015). The drivers representing farmer behaviour and practice did not fit the existing groups. Hence, farm characteristics were added to the existing groups.

Step 4. Expert feedback and consistency check

The creativity, salience, richness, and consistency of scenarios can be enhanced by engaging various stakeholders in the development process (Alcamo, 2008). Furthermore, stakeholder engagement may reduce unintended bias from personal backgrounds, interests and professional knowledge (Ernst et al., 2018). Hence, experts were invited to give feedback on the system diagram developed in Step 3. A questionnaire was developed based on the system diagram to get structured feedback from the experts (presented in SM 2.2). The questionnaire was sent to 30 experts with expertise in pesticide production, use, emissions and risk from research institutes, universities, industries and regulators across Europe. The questionnaire was answered by a diverse group of 20 experts. The expert feedback (presented in SM 2.3) was used to revise the system diagram by rephrasing the existing drivers and including new drivers.

Step 5. Determine scenario logic and critical uncertainties

The identified drivers and status quo from steps 2-4 were used to outline the baseline scenario logic for pesticide use. The system diagram developed in steps 3-4 was used to understand if a particular driver has a positive or negative influence on pesticide use. The scenario logic was developed by analysing the interactions between individual drivers and how they affect pesticide use (e.g. increasing crop production affects cropland area, which further impacts total pesticide use). Pesticide use was defined as a product of two direct drivers: pesticide intensity and cropland area. The drivers influencing pesticide intensity and cropland area were used to summarise the total effect on pesticide use. Next, critical uncertainties were assessed by emphasising if the driver has a positive or negative effect (e.g. economic growth typically coincides with higher consumption levels, leading to more agricultural production and higher pesticide use; however, following the Environmental Kuznets curve theory, richer populations typically demand stricter environmental regulation leading to a decrease in pesticide use).

Step 6. Develop scenario storylines

Future pesticide use is closely related to the development of agriculture and food systems. Therefore, we align the identified drivers to the storyline elements of the Eur-Agri-SSPs (Mitter et al., 2020). The Eur-Agri-SSPs extend the global SSPs with a regional and sectoral component and reflect the structure of the SSPs (Fig. 2). The Eur-Agri-SSPs describe plausible socio-economic, technological and environmental changes affecting European agriculture and food systems. In particular, they outline five scenarios indicating low, medium

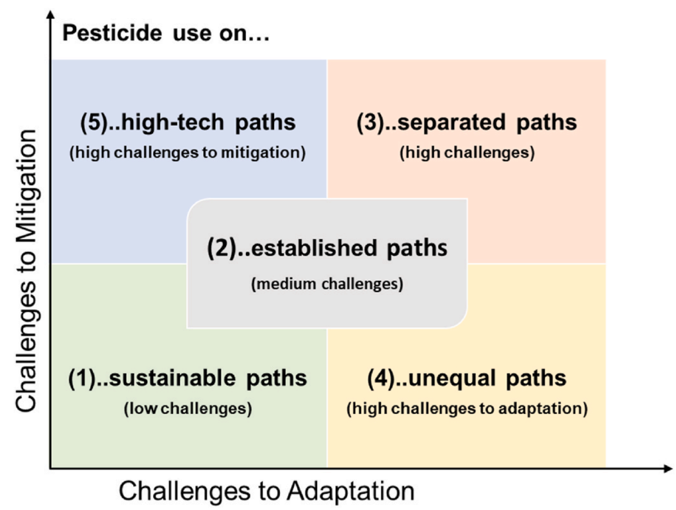

Fig. 2. The scenario matrix for the Pesticide Agricultural Shared Socio-economic Pathways (based on O'Neill et al., 2015; Jiang and O'Neill, 2017; Mitter et al., 2020).

and high challenges to climate change mitigation and adaptation. The storylines are associated with five major thematic groups: (i) population and urbanisation, (ii) economy, (iii) policies and institutions, (iv) technology, and (v) environment and natural resources (Mitter et al., 2019, 2020).

Then the influence of the storyline elements of the Eur-Agri-SSPs on the drivers of pesticide use was determined. Based on the Eur-Agri-SSP scenario logic, the drivers were used to evaluate plausible directions of change in pesticide use up to 2050. Not all drivers of pesticide use were part of the existing storyline elements in the Eur-Agri-SSPs. For such drivers, the future trajectories were either extracted from the Integrated Model to Assess the Global Environment (IMAGE) projections for SSPs in Europe (Bijl et al., 2017; Dellink et al., 2017; Doelman et al., 2018; KC and Lutz, 2017; Popp et al., 2017; Stehfest et al., 2014) or based on scenario matrix. Finally, the Pesticide Agricultural Shared Socio-Economic Pathways (Pest-Agri-SSP) are sketched in alignment with the scenario matrix (Fig. 2) and the future trajectories of drivers of pesticide use (all presented in Table 2).

3. Results and discussions

This section illustrates the results and discussion following the different scenario development steps presented in Fig. 1. The working steps, steps 3 and 4, are iterative in practice. However, to avoid repetition, step 4 is presented first in section 3.3. Then section 3.4 shows the system diagram including the expert feedback.

3.1. Focal issue of the Pesticide Agricultural Shared Socio-economic Pathways (Pest- Agri-SSPs)

The focal issue of the Pest-Agri-SSPs is to present a set of five scenarios consistent with the global SSPs and the Eur-Agri-SSPs but designed explicitly for pesticide use in agriculture (Table 1). The Pest-Agri-SSPs present semi-quantitative trends of pesticide use up to 2050, depending on the changes in the drivers (See SM 1–4). The drivers of the Pest-Agri-SSPs can be quantified for use in integrated assessments of future pesticide use.

3.2. Identify the drivers of pesticide use

The literature review of 97 peer-reviewed articles resulted in 55 drivers of pesticide use ranging from farm to continental scale. SM 1–2 and SM 1–5 present a table with the full list of drivers and the literature used, respectively. At the farm scale, major drivers are agricultural practices, pest pressure, price of agricultural inputs and pesticide application rate. International and national agreements, pesticide approval strategies and maintaining agricultural and food supply chains showed a more considerable influence continentally. Climate change is considered a significant indirect driver of pesticide use because it influences other major drivers such as pest pressure, crop type, pest control strategies, and food security. Overall, the review resulted in a wide array of drivers, potential strategies for reducing pesticide use, and policy goals.

3.3. Expert feedback and consistency check

The questionnaire results confirmed that most experts agreed on the usefulness and correctness of the system diagram for scenario development. The expert questionnaire and results are presented in SM 2.2, including the individual expert comments (SM 2.3). However, based on the feedback, we revised the system diagram to include new and improved definitions of selected drivers. Several experts highlighted farm type and agricultural practice as critical drivers, while others emphasised the importance of technology, policy and climate change. The initial naming of the thematic group farm demographics was changed to farm characteristics to broadly include farmer demographics (e.g. age, education, awareness), farm type, agricultural practice and relative prices of agricultural inputs. The drivers' occurrence of invasive species and pest density were combined to indicate pest pressure in the thematic group environment. Crop as a driver was divided into crop types indicating their relative shares and cropland areas to add clarity and signify their individual influence. Precision agriculture, agroecology and non-chemical alternatives were added to the thematic group technology. The experts recommended renaming the driver international agreements to national and international agreements and agro-payments to agri-environmental payments in the thematic group policy and institutions. Environmental quality standards were added to the system diagram to emphasise policies that ensure air, water and environmental quality. Food standards were changed to crop quality standards to be more comprehensive and include standards established for food, industrial, ornamental and permanent crops by regulatory authorities, retailers and consumers. The driver waste supply chain was changed in the socio-economics thematic group to supply chain waste to refer to the loss and wastage of agricultural products throughout the supply chain.

The expert feedback emphasised the influence of different actors on the type and quantity of pesticides used. The system diagram was modified to include farmers, environmentalists, industries, policymakers, researchers, media, retailers and consumers to explicitly discuss the multiple actors in the pesticide use dynamics. The actors can interact and influence various drivers of pesticide use across the five thematic groups farm characteristics, environment, technology, policy and institutions and socio-economics. For instance, policymakers influence international and national agreements, environmental quality standards and implementation of Integrated Pest Management (IPM). Retailers influence the quality standards of crops, and consumers affect the demand for organic products. Industries impact the pesticide application rate and frequency through labelling and instructions on pesticide products.

The 55 drivers resulting from the literature review were refined by checking if they could present a semi-quantitative trend or direction to be used for modelling purposes. Additionally, multiple drivers indicating similar meanings were excluded, e.g. pesticide application rate and frequency with pesticide intensity and pesticide volume with pesticide use. Further, some drivers were grouped, e.g. agricultural practices comprise tillage, crop rotation and monoculture. Finally, 30 drivers broadly representing pesticide use were selected and grouped into five thematic groups (Fig. 3). The groups of technology and policy, and institutions are consistent with the naming in Eur-Agri-SSPs. The groups of farm characteristics, environment, and socio-economics were renamed and adjusted to include drivers of pesticide use. Overall, ten storyline elements of the Eur-Agri-SSPs were conform to the drivers identified from the literature review.

Table 1
Key characteristics of the Pest-Agri-SSPs.

	Pest-Agri-SSPs
Focal issue	Provide a set of scenarios for pesticide use in agriculture. Extend the Eur-Agri-SSPs by adding drivers related to pesticide use in a systematic way. Provide scenarios that can be applied to similar uses of pesticides in agriculture, such as insecticides, fungicides, herbicides, nematicides and plant growth regulators.
Spatial scale	Europe
Time scale	Up to 2050
Methods	Developed based on a literature review, structured expert feedback and existing storylines. Expert feedback from researchers, policymakers and industry representatives using a structured questionnaire.
Scenario type	Storylines and semi-quantitative trends as a link to integrated assessments.
Similarity to other SSPs	Consistent with Eur-Agri-SSPs. Few drivers are aligned with the global SSPs when the driver is not addressed in the Eur-Agri-SSPs.

3.4. Develop the system diagram for pesticide use

The system diagram in Fig. 3 benefitted from expert feedback. It is clustered into five thematic groups (i) farm characteristics, (ii) environment, (iii) technology, (iv) policy and institutions, and (v) socio-economics. The sets of drivers in the five thematic groups influence either pesticide intensity or cropland area, or both. The combined influence of pesticide intensity or cropland area is the total effect on pesticide use. The actors form an essential component of the system diagram as they influence several drivers of pesticide use at the same time. The grey band represents the zone of influence and presents actors from producers to consumers in the agricultural and food supply chain.

The first group is farm characteristics, in which drivers influencing farmers' behaviour and practices that affect pesticide intensity and cropland area are emphasised. The farmer's behaviour and practices refer to farmer demographics, farm type, agricultural practice and relative prices of agricultural inputs. Farmer demographics encompass the average age of the farmer, environmental awareness and level of education, which influences the decision-making process. The farm type includes the shares of conventional or organic farming (Brückler et al., 2017; Meuwissen et al., 2019). Agriculture practice includes the type of

Table 2
Summary of drivers with positive (+), negative (−), ambiguity (±), no (0) or (?) unknown influence on pesticide intensity, cropland area and pesticide use. The driver trends are presented for the five SSPs as an increase (↗), stable (→) or decrease (↘). Multiplying the direction of the driver trend with (+), (−), (±) or (0) influence gives the trend in pesticide intensity, cropland and pesticide use. The driver trends are either derived from references or based on the scenario matrix.

Drivers			Pesticide intensity	Cropland area	Pesticide use	Driver trend					
						SSP1	SSP2	SSP3	SSP4	SSP5	Reference
Farm characteristics	Farmer demographics	Average age	+	0	+	↘	→	→	→	↘	(Mitter et al., 2020)
		Social status	-	+/-	-	↗	→	→	→	→	
		Educational level	-	0	-	↗	↗	→	→	↗	
		Environmental awareness	-	0	-	↗	↗	↘	↘	↘	
		Labour skills & productivity	-	0	-	↗	↗	→	→	↗	
	Farm type	Growth rate in the share of Conventional farming	+	+	+	↘	→	↗	↗	↘	Scenario matrix
		Growth rate in the share of Organic farming	-	+	-	↗	↗	↘	↘	↗	
	Agricultural practice	Share of area with conservational tillage	-	0	-	↗	→	↘	↘	↗	
		Crop rotation	-	0	-	↗	→	↘	→	↗	
		Monoculture area	+	0	+	↘	→	↗	↗	→	
	Relative prices of agricultural input	Pesticide input	-	?	-	↗	→	↗	↗	↘	(Mitter et al., 2020)
		Non-pesticide agricultural input	+	-	+/-	↗	→	↗	↗	↘	
Socio-economics	Agricultural demand	Population	0	+	+	→	→	↘	→	↗	(KC and Lutz, 2017)
		Economic growth rate (GDP-PPP)	-	+	+/-	→	→	↘	→	↗	(Dellink et al., 2017)
		European import of agricultural commodities	0	-	-	↘	→	↘	↗	↗	(Mitter et al., 2020)
		European export of agricultural commodities	+	+	+	↘	→	↘	↗	↗	
		Relative price of agricultural commodities to 2000	+	+	+	↗	→	↗	→	→	
		Consumer preference for organic produce	-	+	+/-	↗	→	↘	↘	↗	Scenario matrix
		Consumer transition to plant-based diets	?	-	-	↗	→	↘	→	→	
	Landuse		+/-	+	+	↗	↗	↗	↗	↗	(Popp et al., 2017)
	Crop yield		+	-	+/-	↗	→	→	↗	↗	(Mitter et al., 2020)
	Relative share of crops produced	Food crops	-	0	-	↗	↗	↗	↗	↗	(Doelman et al., 2018)
		Industrial crops	+	0	+	↗	↗	↗	↗	↗	
		Flower& ornamental crops	-	0	-	↗	↗	↗	↗	↗	
		Permanent crops	+	0	+	↗	↗	↗	↗	↗	
	Supply chain waste		+	+	+	↘	→	→	↘	→	Scenario matrix
Policies and institutions	International and national trade agreements	Total trade of agri-food commodities	+/-	+/-	+/-	↗	↗	↘	↗	↗	(Mitter et al., 2020)
		Quality schemes for agri-food trade	-	?	-	↗	↗	↘	↗	↗	Scenario matrix
		Pesticide reduction targets in National action plan	-	0	-	↗	↗	↘	↗	↗	
	Agri-environmental payments		-	+/-	-	↗	→	↘	↘	↘	(Mitter et al., 2020)
	Environmental Quality standards		-	-	-	↗	↗	↘	↘	↘	
	Maximum pesticide residual limits on food crops		+	0	+	↘	→	→	→	→	
	Quality standards for crops		-	0	-	↗	↗	→	→	↗	Scenario matrix
	Approved pesticide application dosage		+	0	+	↘	→	→	→	→	
	Registration schemes for pesticide approval		-	0	-	↗	↗	↘	→	→	
	Decision support and forecast on pest outbreak		-	0	-	↗	↗	↘	↘	↗	
	Labelling requirements on pesticide packaging		-	0	-	↗	↗	↘	→	→	
	Labelling requirements on food packaging		-	0	-	↗	↗	↘	→	→	
Technology	Use of precision agricultural techniques		-	0	-	↗	→	↘	↗	↗	
	Use of IPM techniques		-	0	-	↗	→	↘	↗	↗	
	Improvements in pesticide efficiency		-	0	-	↗	→	→	→	↗	
	Use of non-chemical pesticide alternative		-	0	-	↗	→	↘	→	↗	
	Use of agro-ecological techniques		-	0	-	↗	↗	↘	↘	→	
Environment	Pest pressure		+	+	+	↘	→	↗	↗	↗	
	Pest resistance to pesticides		+	0	+	↘	↗	↗	↗	↘	
	Resource depletion		+/-	+/-	+/-	↘	↗	↗	↗	↗	(Mitter et al., 2020)
	Climate change		+	+	+	↗	↗	↗	↗	↗	Scenario matrix

tillage, crop rotation or monoculture (Bonnet et al., 2021; Elias et al., 2018; Meissle et al., 2010), and relative prices of agricultural inputs refer to prices of inputs such as labour, machinery and pesticides. These drivers impact the pesticide application and can be influenced by other drivers such as pest damage, technology, agricultural policies, and agriculture demand and production.

The environment is the second group in Fig. 3, representing the drivers influencing pest damage, indicating crop loss due to pests or

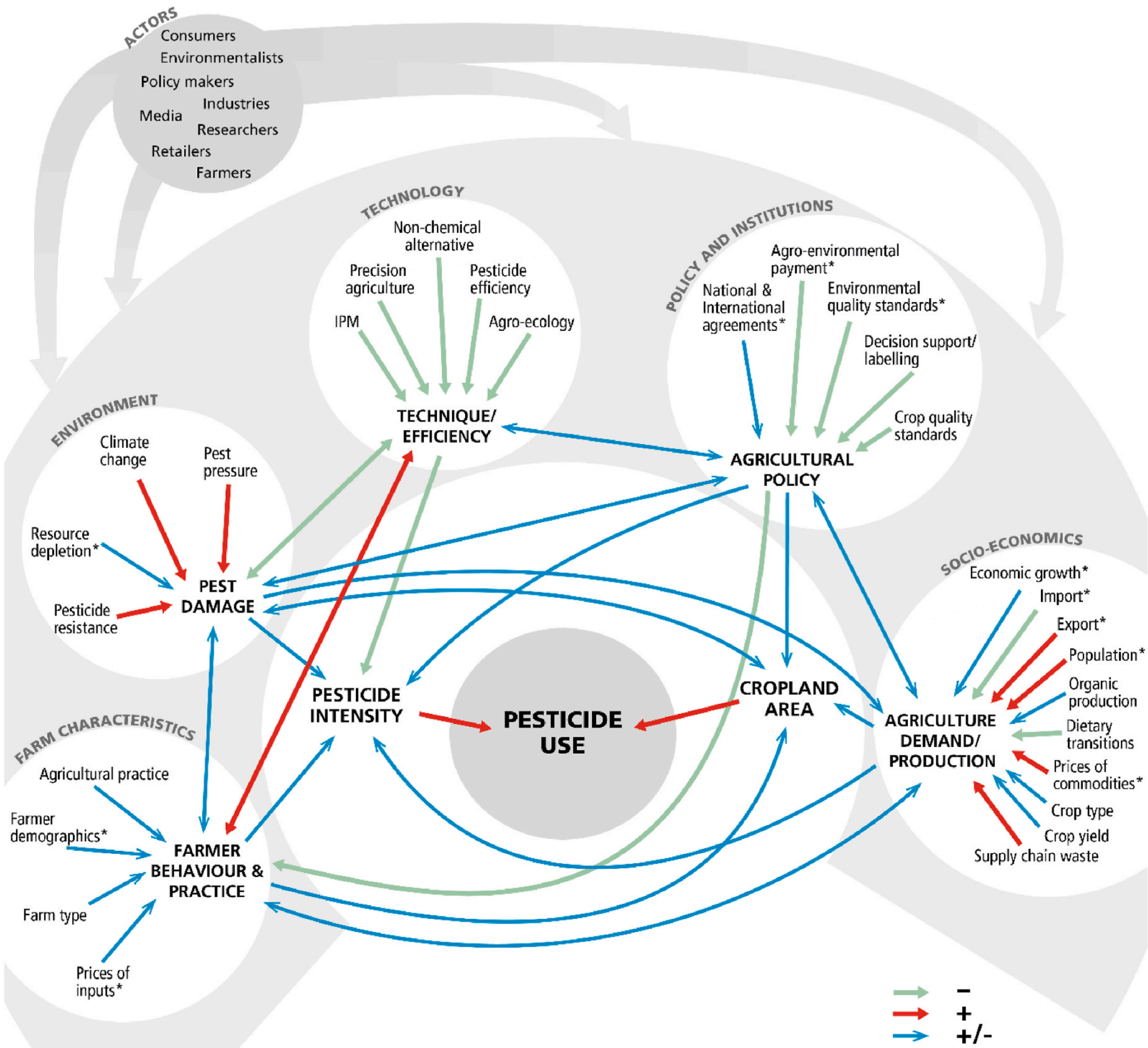

Fig. 3. System diagram presenting drivers of pesticide use and the interaction between them (*indicates drivers that are similar to the Eur-Agri-SSPs, and the grey border indicates the various actors influencing the drivers across five thematic groups).

weeds. Climate change and pest pressure are considered significant drivers of pesticide use. Climate change and related higher temperatures and droughts increase the pest survival rate, causing higher pest pressure (Bebber et al., 2013; Skendžić et al., 2021). Additionally, increases in the frequency and intensity of precipitation can cause the wash-off of applied pesticides and lead to increasing pesticide application frequency (Chaplain et al., 2011). Climate change can further increase resource depletion causing pesticide emissions to different environmental compartments. The pesticide-induced pest resistance (Bakker et al., 2020) and depletion of beneficial insect populations can aggravate farmers' pesticide dependencies. Environmental drivers can directly affect agriculture production by impacting crop yield.

Technological drivers influence the technique of pesticide application and pesticide use efficiency. For instance, precision agriculture is considered as the core element of sustainable agriculture. It comprises site-specific pesticide applications (e.g. drone applicators, sensors for monitoring) (Rajmis et al., 2022) and novel agrochemicals (e.g. nano pesticides) (Kookana et al., 2014) to reduce pesticide use. IPM is a paradigm for crop protection, officially endorsed by many national and intergovernmental bodies (e.g. Sustainable Use of Pesticides, Directive 2009/128/EC, 2009/128/EC, 2009). IPM requires a combination of techniques, such as using resistant cultivars, healthy seeds, crop rotation, biological control and preventive measures like forecasting pest outbreaks (Deguine et al., 2021; Stenberg, 2017; Vilvert et al., 2022). Similarly, agroecological protection refers to a broad range of agroecological principles to reduce pesticide use (Alletto et al., 2022; Poux and Aubert, 2018; Wyckhuys et al., 2022). Additional drivers refer to using non-chemical alternatives such as biopesticides and improving the efficiency of currently approved synthetic pesticides.

Policy and institutions summarise different regulatory drivers that can influence pesticide use. They highlight the mandatory actions that the producers and government officials must undertake to check for compliance. The national & international agreements refer to multilateral agreements that define crop standards in the EU and third countries with pesticide active ingredient use and Maximum Residual Limits (MRL) on crops. These agreements also include European strategies and directives, such as the National action plans, the sustainable use of pesticides (Directive 2009/128/EC, 2009) and the EU Green Deal (European Commission, 2020). Agri-environmental payments are part of the Common Agricultural Policy (CAP), which aims to support EU farmers in achieving the EU Green Deal targets. Additionally, levying pesticide taxes can change farmers' behaviour. Further, pesticide tax is used to pay for farm aid programs and prevent the use of synthetic pesticides in agriculture. The policies shall ensure that the environmental quality standards are met and reduce the risk and impacts of pesticide use on the environment (Directive 2008/105/EC, 2008).

Similarly, the applied pesticide levels on crops are regulated through MRLs (Regulation (EC) No 396/2005, 2005). The EU regulates the approval of active pesticide ingredients through thorough risk evaluation and registration schemes (Council Directive 91/414/EEC, 1991; Regulation (EC) No 1107/2009, 2009). As a result, pesticide ingredients need to be labelled with instructions of use on the packaging that helps in the pesticide application process and for consumer awareness on food packaging. Several European countries provide decision aid on the type of pesticides effective to control a particular pest, forecast pest outbreaks and approved dosage of pesticide application.

The socio-economics thematic group consists of drivers impacting agricultural demand and production. Economic growth has a positive effect on pesticide use. The correlation turns negative following the concepts of the environmental Kuznets curve (Wyckhuys et al., 2022). The trade of agricultural commodities can affect demand, thereby, pesticide use. Population affects the demand for agricultural commodities. Dietary transitions indicate the shift of consumer preference to a plant-based diet, which increases the demand for vegetables and protein-rich crops. The consumer preference to buy organic products influences organic crop production. Depending on the relative share of crop type produced, arable or permanent, pest damage and pesticide dependencies can differ. Permanent crops are typically treated with more pesticides than arable crops, as agricultural practices like crop rotation can reduce pest damage. Supply chain waste refers to pesticide use for reasons of quality maintenance of agricultural products throughout the supply chain, i.e. from farm to consumer.

Finally, pesticide use is expressed as the product pesticide intensity and cropland area. The pesticide intensity is a combination of pesticide application rate and frequency. The pesticide intensity is further influenced by other drivers such as farmers' decisions, pest damage, technique and efficiency of pesticide application and policies. The cropland area is the total land use area for growing arable and permanent crops. The cropland area is influenced by agricultural demand and production, agricultural policy, pest damage and farmer behaviour and practices. The drivers in the five groups can further interact and influence each other (Fig. 3).

3.5. Determine scenario logic and critical uncertainties

The system diagram presents the interactions between the identified drivers and their effect on pesticide use (Fig. 3). It forms the basis to define the scenario logic, by elaborating on individual drivers and their influence on pesticide intensity and cropland area, which then determine pesticide use (Table 2). The drivers in Table 2 are summarised following the five thematic groups and present their individual influence on pesticide use. The drivers can have a positive (+), negative (−), ambiguous (±), no (0) or unknown (?) effect on pesticide intensity and cropland area. The drivers having positive (+) or negative (−) effects are primarily derived from the literature with references included in SM 1–2 and SM 1–5. The ambiguous, no and unknown effects were derived from expert discussion or is a result from multiplying pesticide intensity and cropland area.

The scenario logic refers to the overall story of how the drivers develop. A positive sign indicates that the direction of change of the driver and pesticide use are the same. The negative sign indicates that if the driver increases, pesticide use decreases. When the driver has both positive and negative signs in Table 2, such as for economic growth rate having a negative effect on pesticide intensity but a positive effect on cropland, then pesticide use can either increase or decrease depending on the net effect from pesticide intensity decrease versus cropland increase.

The scenario logic helps to identify the change in pesticide use following the changes in the drivers. Critical uncertainties with the established scenario logic were noted and considered in the next step. For instance, crop yield and pesticide use are positively correlated. However, this positive correlation is limited by a maximum application limit with approved dosage, MRL and quality standards for crops. Another uncertainty was whether a driver has the same influence on pesticide use in all five scenarios, especially for drivers with positive and negative influences (Table 2).

3.6. Pesticide use scenarios: Pest-Agri-SSPs

The pesticide use scenarios are developed based on the individual drivers summarised in Table 2 and their trends across the Eur-Agri-SSPs (driver trend). Drivers not included in the Eur-Agri-SSPs follow the driver trends of SSPs projections from the IMAGE model (Van Vuuren et al., 2021). Drivers not part of both Eur-Agri-SSPs and the SSPs show a baseline trend for SSP2 based on the literature review (references in SM 1–2 and SM 1–3) or information from Eurostat (Eurostat, 2022) (references in SM 2.4) when available. For such drivers, the future trends for SSP1, SSP3, SSP4 and SSP5 are derived based on the scenario matrix (Fig. 2) and are indicated in the last column in Table 2.

The pesticide use trend for Pest-Agri-SSP1, Pest-Agri-SSP2, Pest-Agri-SSP3, Pest-Agri-SSP4, and Pest-Agri-SSP5 can be derived by multiplying the + or – of pesticide use with the trend in the drivers. The + in pesticide use indicates that the pesticide use trend for that SSP is the same as the driver trend. The - in pesticide use indicates that the pesticide use trend for that SSP is the opposite of the driver trend. The pesticide use trends for Pest-Agri-SSP1 to Pest-Agri-SSP5 are further presented in SM 1–4. The storylines are elaborated following the individual driver trend as shown in Table 2. A summary of the Pest-Agri-SSPs under the influence of farm characteristics, socio-economics, policy and institutions, technology and environment is presented in Fig. 4.

3.6.1. Pest-Agri-SSP1 (Pesticide use on sustainable paths)

The agricultural and food systems develop on sustainable paths, driven mainly by higher education levels and environmental awareness. Farm demographics with better social status and younger farming populations emphasise the flexibility to adapt to new techniques. Agricultural practices are shifting towards organic farming and reduced tillage approach to reduce synthetic pesticide use. The European population remains constant, and economic growth rates stabilise. Import and export quantities of agricultural commodities are decreasing. Consumption is oriented towards less consumption of animal products and shifts towards organic products. Dietary shift to non-meat consumption increases demand for fresh and seasonal food. On the contrary, demand for industrial and bio-energy crops reduces. Waste along the agricultural supply chain reduces. European policies progress towards better international and national environmental policies. Higher environmental standards reduce pesticide application dosages and stricter registration schemes and labelling. Increasing agro-environmental payments helps in the potential reduction of pesticide use. Growing cooperation between different actors, farmers, policymakers and industries assists in a better decision support system to manage pest pressure. The technology progresses towards lower emissions, energy efficiency, and chemical pesticide-free agriculture. Substantial technological investments lead to higher pesticide efficiencies and improved precision farming practices. Best available techniques, such as agroecological practices and IPM, are incorporated. The focus on using non-chemical alternatives increases, owing to consumer demand. Land use is strongly regulated to avoid environmental trade-offs. Climate change increases pest pressure, but sustainable agricultural practices help reduce pesticide use. The Pest outbreak and resistance decrease, leading to higher crop yields. The overall pesticide use is expected to decrease in SSP1 by analysing the trends of all different drivers (Fig. 4), with seven positive and 37 negative trends reported.

3.6.2. Pest-Agri-SSP2 (Pesticide use on established paths)

The development in the agricultural and food systems follows the historical patterns resulting in moderate but steady social, environmental and technological progress. Environmental awareness among

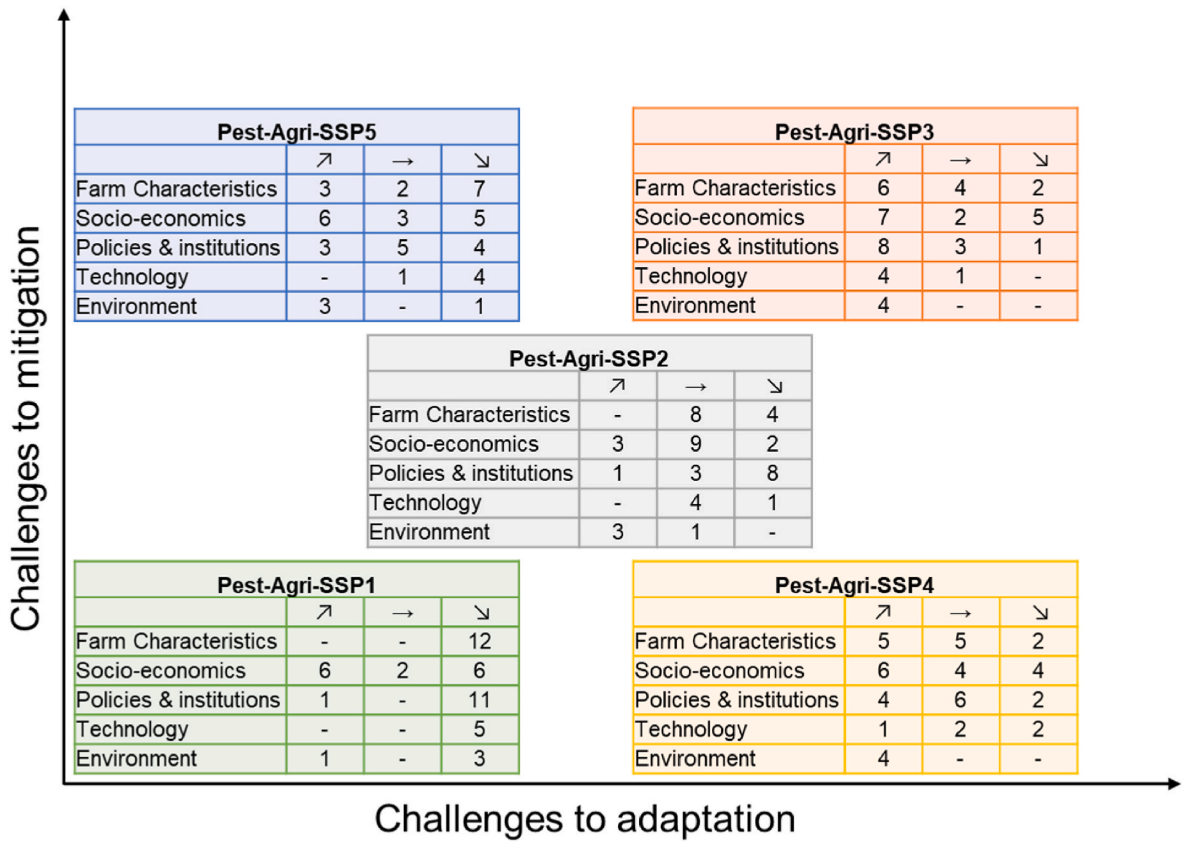

Fig. 4. Summary of the five Pest-Agri-SSPs by thematic groups of driver. The ↗ indicates an increase, → stable and ↘ decrease in pesticide use. The numbers represent the count of ↗, → and ↘ pesticide use trends per driver group.

farmers slowly increases; however, social status does not improve. There is a slow shift to new techniques among the farming population owing to the social status and relative prices of agricultural inputs. The agricultural practices follow the current conventional and organic farming patterns, including traditional crop rotations. However, the percentage of area under organic farming practices across Europe remains considerably lower. Moderate economic and population growth sustains agricultural commodities' current demand. Consumer preference is slowly transforming towards non-meat diets and local and organic produce. There is national and international cooperation on agreements following European policies. The environmental and crop quality standards are increasing. The policies are moving towards stricter pesticide registration schemes, improving decision support on pest outbreaks and pesticide application. The investment in research and technology to promote sustainable development remain slow but continuous. There are better precision agriculture techniques and IPM, which help gradually reduce pesticide use. Technology acceptance is relatively slow by both producers and consumers. The effects of climate change have a moderate impact posing pest pressure and increasing pest resistance. Though there are strict policies in place, resource depletion continues. The changes in land use steadily follow the historic trends owed to existing imports and exports. In Pest-Eur-Agri-SSP2, pesticide use would follow the current pattern leading to further increased pesticide usage, indicated by the 25 stable trends in drivers (Fig. 4).

3.6.3. *Pest-Agri-SSP3 (Pesticide use on separated paths)*

The Pest-Agri-SSP3 presents regional rivalry and mistrust across countries in Europe and outside. Growing concerns concerning international competitiveness and national security push societies to become more sceptical about globalisation and focus on regional issues (Mitter et al., 2020). With decreasing environmental awareness among farmers, education and labour supply are reduced, forcing them to switch to pesticide-intensive agriculture. Decline economic growth and dwindling population across regions result in stagnating agricultural demand. Lower import and export of agricultural commodities and higher food security issues causes increased demand and stress on local agricultural production, intensifying pesticide use to improve yield. The customer preference for organic produce and non-meat diets weakens. Lower national and international cooperation on trade agreements leads to reduced quality standards in agri-food trade. Restricting cooperation in European countries results in abandoned common agricultural policy and environmental standards. The existing quality standards for crops and registration schemes remain. Land use increases with higher land grabbing due to low protected areas. Confidence between agricultural producers and consumers reduces. Technology development is prolonged due to low investment levels leading to the use of existing pesticides and no innovation in non-chemical alternatives. Technology uptake in agriculture decreases, causing reduced use of precision agriculture and IPM techniques. Pesticide efficiency remains stable with no technological improvement, causing higher pesticide application with the influence of climate extremes. The risk of pest outbreak and pest resistance significantly rises with higher temperatures. The excessive use of pesticides to maintain crop yield causes increased depletion of resources. The pesticide use is expected to intensify excessively in Pest-Agri-SSP3, resulting from the influence of different drivers (Fig. 4), with in total of 29 increases in driver trends.

3.6.4. *Pest-Agri-SSP4 (Pesticide use on unequal paths)*

The agriculture and food systems develop with increasing social disparities and fragmentation of society with inequalities. Education opportunities are unequal. Average farming age and social status remain relatively stable. Environmental awareness is limited to middle and high-earning groups. The shift to organic farming and efficient tillage practices reduces with a general decrease in environmental awareness.

Though the existing crop rotation prevails, the productive areas are dominated by industrialised agriculture and monocultural production. Monoculture would lead to higher pest damage causing increased pesticide use. Lower attention to environmental problems and sustainable agricultural practices demands higher pesticide use.

In comparison, rising prices of agricultural inputs cause a partial decline in pesticide application. Population growth in Europe stagnates with moderate economic growth, posing no significant changes in agricultural demand and pesticide use. The import and export of agricultural commodities strengthen in Europe. High pesticide application to preserve crops along the supply chain. A dietary shift toward lower meat consumption and organic produce is restricted to the higher-earning group due to higher prices and awareness, causing an increase in pesticide use. The regulation in the agriculture sector stagnates, triggering no improvements in the existing pesticide policies for registration, labelling or decision support. The agro-environment payments reduce for less privileged farmers. Crop yields would be typically high in large-scale industrial farming but low for small-scale farming. Technology development in agriculture, precision farming, and IPM is slowly progressing. However, due to social disparities, the availability of technologies and acceptance distribution is considerably lower due to low awareness and education levels. Climate change poses added pressure on the agricultural and food systems, aggravating pest damage and resistance. These factors further push pesticide use and resource depletion. In general, the pesticide use pattern in Pest-Agri-SSP4 presents a substantial increase and decrease in pesticide use (Fig. 4), with 20 increases and 17 decreases in driver trends.

3.6.5. Pest-Agri-SSP5 (Pesticide use on high-tech paths)

The Pest-Agri-SSP5 presents the development of agriculture and food systems in high-tech paths. Technological progress is considered a significant driver of development and economic growth. The European population is increasing along with growing international immigration to Europe. The increasing education levels and the decreasing average of the farming population are leading the way for a generational change in the agriculture and food systems. It drives high-tech machinery and input, expanding agricultural practices with organic farming and conservational tillage. Globally integrated markets enhance the import and export of agricultural goods from Europe. However, this poses added pressure on the agriculture and food systems and pesticide use. Consumer demand shifts toward organic produce and bio-products, forcing a reduction in pesticide use. The national and international agreements on agri-food trade increase but warranting quality standards and pesticide reduction plans decrease. The agri-environmental payments and environmental standards decline. The socioenvironmental focus policies remain the same. Though crop quality standards increase, pesticide policies for approval, registration and labelling endure. Pesticide use is rising due to extreme climatic conditions leading to higher pest pressure. Reducing environmental awareness and climate events enhances the frequency of pesticide application. However, better technology owes to higher pesticide efficiencies and the presence of non-chemical alternatives leading to a reduced pesticide application rate. Environmental standards are considerably low, which results in the overexploitation of natural resources. In total, the Pest-Agri-SSP5 presents a decline in pesticide use with 21 decreasing and 15 increasing driver trends (Fig. 4).

3.7. Comparison of Pest-Agri-SSPs and Eur-Agri-SSPs

The Pest-Agri-SSPs look at pesticide use as a combination of farm characteristics, environment, technology, policy and institutions and socio-economic drivers in five future scenarios. They extend and enrich the Eur-Agri-SSPs by adding pesticide use in the agriculture and food systems in a systematic way. They provide a set of alternative future developments with semi-quantitative pesticide use trends. The Pest-Agri-SSPs are consistent with the Eur-Agri-SSPs and emphasise the future development of pesticide use in Europe. The Pest-Agri-SSPs provide a platform to make quantitative assumptions required for numerical modelling and evaluating policy targets. Pest-Agri-SSPs connect different actors and their role in driver-based interaction. The developed scenarios account for the policy targets in the European Green Deal, sustainable pesticide use directive and farm-to-fork strategies, including IPM, CAP, registration and labelling.

The Pest-Agri-SSPs detail various technologies such as IPM, novel chemicals and agroecological practices specific to pesticides. Compared to the Eur-Agri-SSPs, the Pest-Agri-SSPs discuss organic farming and changes in conventional farming in all five scenarios as they are relevant to pesticide use. However, the scenarios consider a constant change between organic and conventional farming, dominated mainly by pest damage, relative costs, labour supply and crop yields. Similarly, precision techniques are considered in all the scenarios owing to the current agricultural practice. Technology and environment groups are given less attention in Eur-Agri-SSPs as they can be sector specific. The Pest-Agri-SSPs are more detailed in this respect and identify important technological and environmental drivers of pesticide use. They further include climate change-related impacts on the agriculture and food system. In general, the SSP logic builds on future developments in socio-economic, technological, globalisation and lifestyle change, excluding climate change. However, in the Pest-Agri-SSPs, climate change is considered as it influences multiple drivers of pesticide use. In all the Pest-Agri-SSP scenarios, climate change is expected to increase, as suggested by the historical trend and future projections. However, the extent of climate change differs per scenario, which can be quantified by coupling with the Representative Concentration Pathways (RCPs).

The Pest-Agri-SSP trends are similar to agriculture exposure scenarios (Hader et al., 2022) for SSP1 (declining pesticide use) and SSP3 (large increase in pesticide use). The Pest-Agri-SSPs consider all uses of pesticides in the agriculture and food systems and can be similarly applied to understand pesticide use in other regions of the world.

The Pest-Agri-SSP development steps can be used to understand additional environmental issues, such as fertiliser use and carbon emissions from the agriculture and food systems. The Eur-Agri-SSPs specify drivers critical to the agriculture and food systems allocated to the five thematic groups population and urbanisation, economy, policy and institutions, technology, and environment and natural resources. However, they do not address specific environmental problems. For example, the Eur-Agri-SSPs explains general policies about the agriculture and food systems, while details, e.g. on fertiliser policies, are not included. Similarly, technology development is addressed but lacks details that may be relevant to individual environmental problems.

4. Conclusions

The scenarios developed in this article, the Pest-Agri-SSPs, show plausible pesticide use trends up to 2050 under climate and socio-economic change (Fig. 4). The Pest-Agri-SSPs consider drivers from farm to continental scale in combination with multiple actors impacting them. The scenarios build on a literature review of the main drivers of pesticide use, including agricultural practices, pest pressure, climate, policies and technology. Climate change profoundly influences pesticide use as it can intensify pest pressure and alter the efficiency of technologies and policies. The expert feedback enriched the salience of the drivers such as agricultural practices, novel technologies and pesticide policies at the national and EU levels and reduced unintended biases.

The Pest-Agri-SSPs present five pesticide use scenarios showing low to high challenges for climate change mitigation and adaptation, under the future development of farm characteristics, environment, technology, policy and institutions and socio-economic drivers. The Pest-Agri-SSP1 shows a decrease in pesticide use owing to technological advances and strong implementation of EU policy targets. On the contrary, Pest-Agri-SSP3 and Pest-Agri-SSP4 show an increasing trend in pesticide use. The Pest-Agri-SSP2 presents a stable trend compared to the other scenarios, as it follows the current trend to ensure food security with rising environmental awareness and technological progress. The Pest-Agri-SSP3 shows a substantial intensification in pesticide use. Though there is a general surge in pesticide use in Pest-Agri-SSP4, it presents a mix of increasing and decreasing trends. The unequal distribution hinders substantial improvements in technology and farming practices, making it challenging to achieve EU policy targets to their full potential. The Pest-Agri-SSP5 presents an overall decreasing trend owing to technological developments and sustainable agricultural practices, but meeting demand for agricultural commodities given the impacts of climate change increases the use of pesticides. The developed Pest-Agri-SSPs account for the EU policy targets considered in the EU green deal, sustainable pesticide use directive and farm-to-fork strategies such as IPM, CAP, registration and labelling. The Pest-Agri-SSPs provide a platform for further use in quantitative modelling to evaluate pesticide use and policy targets.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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