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Changing the understanding of crop production: Integrating ecosystem services into the production function

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ABSTRACT

Ecosystem services, such as weed and pest regulation provided by biodiversity, are vital for sustainable crop production. However, the economic contributions of biodiversity are often overlooked in commercial markets due to the absence of market prices. This complicates quantification and comparison with physical capital, leading to poor economic decisions. To improve the economic understanding of crop production, we combine economic and ecological analyses and develop a structural production economic model that accounts for ecosystem services' contributions to crop yields. Our structural crop production function integrates both anthropogenic inputs and ecosystem services, quantifying production possibilities along a spectrum from input-intensive to ecosystem service-based management practices. The model explicitly depicts resource allocation decisions across labour, physical capital, and intermediate inputs. To mitigate and reverse biodiversity stressors in intensive agriculture, alternative management practices that maintain productivity while reducing reliance on polluting inputs are essential. We review and recommend economic and ecological indicators, ranging from ideal measurements to available proxies, for model estimation, addressing the trade-offs between accuracy, feasibility, and data collection costs. Our analysis emphasises the need for comprehensive information to operationalise the understanding of productivity and substitutability between ecosystem services and biodiversity-adverse inputs such as agrochemicals and energy.

1. Introduction

Crop yields produced by industrial cropping rely largely on anthropogenic inputs, such as agrochemicals in form of plant protective products (e.g., insecticides, fungicides, and herbicides), mineral fertilisers, and fossil energy necessary for mechanical measures. However, agrochemical inputs pollute the environment, impact human health and the climate, contribute to declines in biodiversity, and degrade ecosystem services (ES) in cropping systems (European Commission, 2020; Goulson et al., 2015; IPBES, 2019; Ramankutty et al., 2018). The same biodiversity which is negatively impacted by high-input agriculture is an inevitable prerequisite for crop production. Its loss causes ever-increasing dependence on anthropogenic inputs and energy resulting in lock-ins (Duflot et al., 2022; Popp et al., 2013; Tscharntke et al., 2012). Functional biodiversity, such as predators feeding on herbivorous pests, is the bases for ES in the crop ecosystem and supports crop production providing crop protection, nutrient cycling, and pollination (Bommarco et al., 2013; Fiedler et al., 2008; Senapathi et al., 2021). Nevertheless, biodiversity and its contributions to human welfare are barely integrated in commercial markets (Costanza et al., 1997; Daily et al., 2000). Consequently, its quantification in economic terms, and in ways comparable with other production factors, remains challenging, despite extensive evidence of the enormous contributions of natural capital and ES for production (Abson et al., 2014; Costanza et al., 1997; Daily, 1997; Norgaard, 2010).

Simply reducing anthropogenic inputs in cropping systems without taking management actions to enhance ES would lead to drastically lower crop yields as disservices, such as pest damage and weed competition, are not mitigated (Foley et al., 2011; Oerke and Dehne, 2004; Popp et al., 2013). ES-based management, such as ecological intensification and agroecological farming, are management practices integrating ecological processes instead of ignoring them or even working against them. The aim of ES-based management is to maintain a balance of beneficial and detrimental species that is favourable for crop

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production, by promoting ES such as biotic weed and pest regulation, and soil ES, while minimising disservices,[1] such as pest damages and weed competition (Altieri, 1999; MacLaren et al., 2021). However, enhancing the provisioning of ES requires management effort and, hence, inputs in form of labour, capital, and intermediate inputs. Explicitly introducing the production value of biodiversity that provides ES in a crop production function enables the quantification and productivity comparison with marketed inputs, such as labour, capital and intermediate inputs. A growing body of research shows that it is possible to reduce the dependence on external inputs while maintaining production by managing the fields to enhance ES provided by biodiversity (Bommarco et al., 2013; Dainese et al., 2019; Tamburini et al., 2020). However, the assets that biodiversity provides are not reflected in farm economics, which leads to a lack of understanding and accounting of the commodity role that wild and managed biodiversity can play in crop production.

Here, we develop a structural, i.e., nested and theoretically grounded, crop production function model at the field scale, which integrates anthropogenic inputs and the contribution of biodiversity in form of ES. Using a standard microeconomic production function as a basis (see e.g., Coelli et al., 2005), we describe production possibilities across a gradient of input-intensive to ES-based management practices. The production function makes resource allocation decisions of farmers explicit and shows the possibilities to choose between managing primarily with anthropogenic inputs or for ES. Financial, business and productivity outcomes are important drivers for farmers' behaviour (Barnes et al., 2022). The model facilitates a comparison of productivity of labour, capital and intermediate inputs conditional on the chosen type of management, i.e., high-input and ES-based management while accounting for the biodiversity-adverse effects of some inputs. We define economic benefits in terms of utility, e.g., through increased or sustainable crop production, without necessarily being expressed in monetary terms.

In this study, we aim to conceptualise an understanding of substitutability, synergies and trade-offs between anthropogenic inputs and ES. We employ the concept of ES when referring to the benefits of biodiversity (see Millennium Ecosystem Assessment, 2005; Power, 2010) to align with the anthropocentric perspective inherent in the production function model. ES are omnipresent in all cropping systems, such as highly input dependent, ecologically intensified, organic, pesticide free, regenerative or no-till farming. However, management to enhance ES differ among cropping systems. By explicitly including the contribution of biodiversity and ES to commodity production, the structural production function enables comparing performance and outcomes of any cropping system. Our model is a tool for empirical analysis of marginal effects and guides the required data collection. As a step towards applicability, we review and propose economic and ecological indicators for empirically estimating the production function. Our overview reaches from the ideal measure to the most readily available indicator, addressing the trade-off between accuracy and feasibility of these indicators.

Inclusions of biodiversity as a production input are scarce (McConnell and Bockstael, 2005). Typically, production economics disaggregates production factors in intermediate inputs (e.g., pesticides, fertiliser and energy), capital inputs (e.g., machinery and land), and labour (Antle and Capalbo, 2001; Carpentier and Letort, 2014; Gardebroek et al., 2010; Hansson et al., 2018; Koiry and Huang, 2023). In these estimations, it is often assumed that basic inputs such as labour and intermediate inputs influence yield in the same way even though intermediate inputs, other than labour, impact bio-physical processes directly, which can lead to biased productivity estimates (Lichtenberg and Zilberman, 1986; Zhengfei et al., 2006). We move beyond the current literature by developing a model that highlights the possibilities to substitute between anthropogenic and ES-based production inputs.

Our model is a part of the economic-ecological or bio-economic modelling, connecting insights from ecology, economics, and agronomy. It emphasises the integration of concepts rather than merely exchanging information (Castro and Lechthaler, 2022; Flichman et al., 2011). Most studies in this field concentrate on individual well-understood ES. Models usually include one or two production factors such as pollination and pest control (Grogan, 2014; Kleftodimos et al., 2021), weed control (Böcker et al., 2019; Gonzalez-Diaz et al., 2020), or soil health (Brady et al., 2015; Brady and Wilhelmsson, & Hedlund., 2019). Agricultural economic models are typically limited to either pesticide or fertiliser use (Lichtenberg and Zilberman, 1986; Zhengfei et al., 2006). A comprehensive overview of the entire economic-ecological production system is lacking (Power, 2010). Here, we extend existing models by portraying a holistic production economic framework of cropping systems including the main biophysical preconditions for crop production that can be impacted by management and their provisioning through ES and anthropogenic inputs.

In the following section, we introduce the ecology of the crop ecosystem to provide the necessary biological background for the production function framework, which will be presented in the third section. Since many aspects of the model are either latent or too complex to measure, section four provides a set of economic and ecological indicators necessary for an empirical estimation of the framework, followed by a discussion and concluding remarks in section five and six.

2. Introducing the crop ecosystem

Cropping systems are ecosystems. Their functioning shares the same ecological principles and energetic dynamics of ecosystems that are not managed by humans (Smith, 2015). The crop ecosystem is composed of compartments interacting with each other (Fig. 1). At the core are cultivated plants, which provide the crop yield. The cultivated plants, part of the managed biodiversity in the field, coexist with wild plants, which, when abundant, are considered as weeds. Herbivores feed on both crops and weeds. The herbivores, in turn, are food resources for predators together with decomposers. Dead plants and insects, crop residues, and excrements flow from the other compartments and become inputs to the soil organic matter (SOM) pool, which is food for decomposers and contributes to the nutrient pool of the system (Fig. 1). Water, atmospheric CO_2, and energy are foundational abiotic factors influencing processes and resource flows in the agroecosystem.

Compartments that have a biotic component harbour communities of organisms with many species and various functions that are either managed, e.g., the crops and their rotation in the field, or naturally occurring (i.e., wild biodiversity). The managed and wild organisms drive flows within and between compartments, underscoring the crucial contribution of biodiversity in ecological processes delivery. Explorations of the link between biodiversity and ecosystem functioning show that ecosystems produce higher biomass and ES with increasing diversity (Bommarco et al., 2013; Cardinale et al., 2011; Dainese et al., 2019). Although all biodiversity is relevant, we refer to biodiversity providing ecosystem functions and resulting in ES as functional biodiversity. Ecosystem functions are "the biotic and abiotic processes that occur within an ecosystem and may contribute to ES either directly or indirectly" (Garland et al., 2021). The functions that we consider and that translate into ES or disservices include predation, competition, decomposition and herbivory (Bradford et al., 2014).

ES of the cropping system are greatly influenced by land use management. Intensive cropping is a main driver of global biodiversity loss (Campbell et al., 2017). There is, however, also a range of cropping practices that can maintain or enhance ES in the short- to long-term (Beillouin et al., 2021; Cozim-Melges et al., 2024; Tamburini et al., 2020). Here we focus on management practices affecting four central

[1] Disservices should be conceived as imbalances occurring due to poor agronomic practices, such as intensive monoculture, which decrease the crop competitiveness with weeds and increase the abundance of pests.

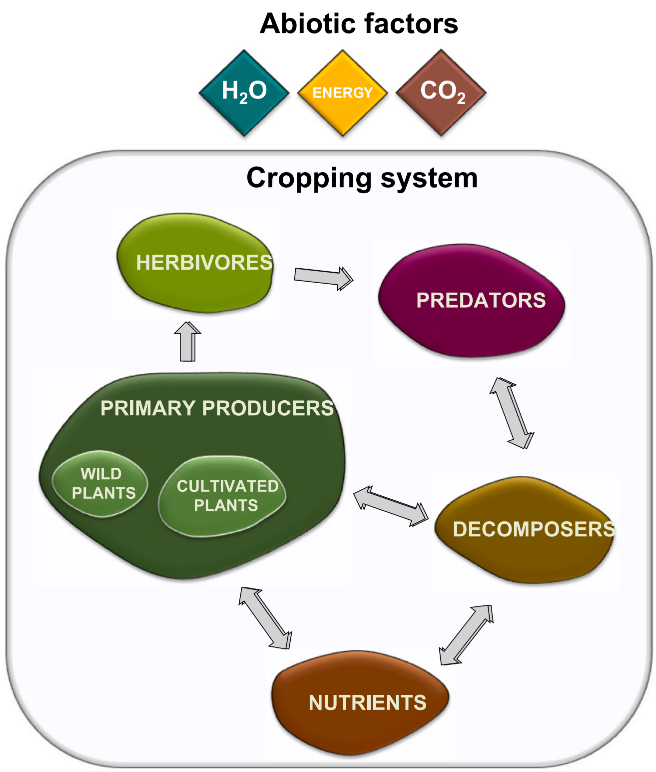

Fig. 1. Main compartments and actors involved in a crop ecosystem. Circles represent ecosystem compartments and arrows the flows between them. Directions of the arrows convey the net direction of energy or matter that flows from one unit to the other. Some additional flows, e.g., from herbivores to decomposers, have been omitted for simplicity.

functions in crop production: net primary production (i.e., crop yield), competition with weeds, herbivory and plant nutrient cycling.

2.1. Net primary production: cultivated plants as primary producers and measures to maintain productivity

Primary production (PP), in an ecological sense, is a fundamental biophysical function. Plants are the main organisms providing PP through photosynthesis, transforming solar energy into chemical form as sugars or more complex compounds. Several factors, including energy, nutrients, water, and interactions with other organisms through herbivory and competition, impact plant primary production and growth (Ngoune Liliane and Shelton Charles, 2020; Pace et al., 2021).

Because the principal aim of cultivating crops is to render food and feed with marketable value, human management aims at minimising yield losses. To maintain production levels, various measures are implemented, which can be categorised as either preventative or corrective. For instance, crop protection can be achieved with corrective measures including all practices aimed at eradicating damaging species, such as applying synthetic plant protective products to suppress a population of herbivores or weeds resurging in the crop field (Popp et al., 2013), or with preventative measures such as diversified farming, reduced disturbance and introducing perennial crops in cropping systems based on annual crops (Bommarco, 2024). These measures aim to regulate the herbivore or weed populations thereby preventing outbreaks (Lundin et al., 2021; Rosa-Schleich et al., 2019).

Based on their effect on the cropping system, it is possible to categorise management practices into corrective and preventative management, both of which can have short- and long-term effects on ES. Annual management implemented in at least one season includes applying pesticides, tilling, fertilising and sowing or planting an annual flower strip. Long-term effects arise when an annual practice is employed over several consecutive years. For instance, pests and weeds develop resistance when pesticides are repeatedly applied, and non-target biodiversity can be negatively affected. If biodiversity-supporting practices are implemented, it can take time for biodiversity and ecological processes to react to the changed management (Alignier and Aviron, 2017). For instance, diverse crop rotations have been shown to increase nutrient-use effectiveness over time eventually outperforming crop sequences with the same crop year after year (e.g., Smith et al., 2023).

In our proposed production function, we consider effects of management on wild and managed biodiversity and the effect this has on ES in the short- to long-term (see Section 4). We classify practices that are (i) annual corrective practices aiming to sustain yields in the short term, e.g., with annual pesticide applications to reduce an emergent pest outbreak with possible negative effects on biodiversity (Jones et al., 2022), (ii) annual preventative practices aimed at benefitting wild and managed biodiversity that provide ES (Duru et al., 2015), and (iii) long-term preventative practices aimed at benefitting wild and managed biodiversity to strengthen the provisioning of ES (Duru et al., 2015; Jonsson et al., 2014).

2.2. Wild plants: weeds competing with yield

Wild plants establish and thrive in the crop ecosystem. When they become abundant, they are considered weeds as they compete with the planted crop for space, nutrients, light, and water, with unfavourable effects on crop yields. About one third of the potential yield is estimated to be lost to weeds (Oerke, 2006). They are particularly adapted to exploit nutrient-rich and disturbed habitats, which are typical of cropping fields. However, wild plants intermixed with crops also provide benefits. They contribute to carbon storage, enhance biodiversity providing resources to pollinators and predators and decrease soil erosion (Gaba et al., 2020; MacLaren et al., 2020; Storkey and Neve, 2018).

Crop protection against weeds (hereafter weed control) is mainly implemented through herbicides (MacLaren et al., 2020). Most breeding efforts are directed towards conventional forms of agriculture, creating herbicide tolerant crops, ultimately complementing genetic material with agrochemical inputs (Hildermann et al., 2009; Lammerts van Bueren et al., 2011). However, using herbicide tolerant crops is considered unpredictable in changing environmental conditions (Steinbrecher and Paul, 2017). Additionally, bans and restrictions against herbicides are increasing (Finger et al., 2023). The use of herbicides and other agrochemicals has an array of unfavourable consequences on water bodies, natural habitats and human health. Further, intensive herbicides use selects for resistance in weeds in the long-term (Beckie and Tardif, 2012). In the light of these consequences and the continuous arms race between technology and wild plants, herbicide usage is becoming less effective because few/no new compounds have been developed since the late 90s (Duke, 2012; Gould et al., 2018). While chemical interventions can offer immediate solutions, relying solely on them in cropping systems is unsustainable in the long term.

Viable alternatives to chemical weed management include tillage, i.e., working the soil to suppress weeds. By disturbing the soil surface, tillage effectively reduces weed growth by displacing the seeds (Armengot et al., 2016). However, tillage can contribute to soil erosion, greenhouse gas emissions and the disruption of important soil functions (Keller et al., 2019; Lobb, 2008; Mangalassery et al., 2014). While tillage is effective in certain cropping systems, it is not by itself a weed management solution.

To tackle the negative effects of and dependence on fossil fuels that come with herbicide use and intensive tillage, weed management based on ecological principles have been suggested (MacLaren et al., 2020). In the short-term perspective, refugia for seed eating insects, such as carabid beetles, can be implemented by the farmer. Planting flower strips can increase the ES delivery of seed predation (Schmied et al., 2023). Cover crops in between main crops are also an annual management practice that can suppress weed emergence, reducing the reliance on chemicals (Büchi et al., 2018). However, since ecological processes typically build over several cropping seasons, long-term strategies such as diversification, e.g., by crop rotation and intercropping (Duchene et al., 2017; Liebman and Dyck, 1993), livestock-crop integration and reduced disturbance show promise to render sustainable weed management solutions (MacLaren et al., 2020).These strategies strengthen ecosystem functions and reduce input needs in the long run (Duru et al., 2015; Storkey et al., 2019). They interrupt the growth cycle of weeds and reduce weed seed viability over the years. Hence, diversified crop rotations and intercropping give more gradual effects than a short-term intervention, but have a deeper and more lasting impact on weed control and soil health (Hosseini et al., 2014; MacLaren et al., 2020).

2.3. Herbivory and predation: animal pests and their antagonists

Crops are bred to be fast growing and nutrient rich. This has come at the expense of their defence against herbivory. Crops are palatable for a range of herbivores and pathogens, such as fungi and viruses. Only a minority of these build large enough populations to cause yield losses, i.e., and therefore are considered pests. Yet, herbivory is one of the most limiting factors to crop primary production, causing losses that range between 17 and 23 % of the yield (Oerke, 2006; Savary et al., 2019). Herbivores are prey to beneficial organisms contributing to the functional biodiversity pool of the cropping system and delivering the pest control service. This dual role of herbivores, as pests and support to organisms providing ES, highlights the importance of applying ecological concepts when managing cropping systems.

Management of pests and pathogens to reduce yield losses (hereafter, pest control) currently relies heavily on the use of pesticides in the dominant cropping systems (Popp et al., 2013), with highest usage per cultivated area in the USA and Europe (FAOSTAT, 2023). Pesticides have well recognised detrimental effects, including toxicity to non-target species, pollution of soil and water, and impacts on human health (Jacquet et al., 2022). Non-target organisms affected by agrochemical use span from algae, fish, and microbes, mostly impacted through chemical leakage and circulation, to beneficial insects inhabiting the crop ecosystem such as pollinators and predators to pests (Sharma et al., 2020). Many countries have therefore implemented risk reduction plans and fixed goals to reduce pesticides, with the ultimate objective of moving away from dependence on inputs that are no longer effective and environmentally unsustainable (Möhring et al., 2020).

The reliance on pesticides can be reduced by strengthening pest regulation generated within the cropping system (Janssen and van Rijn, 2021). Enhanced pest regulation is also possible when different crops are grown in sequences, disrupting the life cycles of herbivores that rely on particular crop species (Jaworski et al., 2023). Annual management for weed control, i.e., intercropping and flower strip planting, has potential application for pest control, by creating adverse conditions for pests, disrupting favourable habitats or increasing predator diversity and abundance at the field scale (Letourneau et al., 2011). Long-term management prioritises fostering a diverse community of predators and antagonists that prey on herbivores as viable alternative to chemical use. Cover crops and low tillage can increase soil macrofauna and hence their services (Kelly et al., 2021). Beneficial communities often develop over time, emphasising the shift from seeking quick fixes to embracing long-term solutions based on ecosystem management. Long-term practices with a higher plant diversity have a significant impact on local biodiversity and soil health while decreasing pest and weed pressure (Bennett et al., 2012; Brady et al., 2015; Isbell et al., 2017; Peralta et al., 2018). Managing functional biodiversity therefore means inverting the trends of crop protection and resorting to chemical inputs only in drastic scenarios, i.e., pest outbreaks above economic thresholds, and not as preventative measure (Lundin et al., 2021).

2.4. Soil fertility: nitrogen available for the plants

Plants extract water and nutrients from the soil. Given constant environmental variables, the fluctuations in plants growth indicates the soil capability to sustain it. This is defined as soil fertility, the property indicating the soil's potential to provide essential resources and support robust plant growth (Daou and Shipley, 2019). Fertile and nurtured soils rely on biotic processes to provide nutrients, before external supplies by anthropogenic inputs. Bacteria, fungi, soil microorganisms and the whole soil biota are therefore indispensable for nutrient mobilisation and availability (Moreau et al., 2019).

The essential nutrients for plants are nitrogen (N), phosphorus (P), and potassium (K). We here focus solely on nitrogen, as plant available nitrogen is often the most limiting factor among the three. Both nitrogen fixation and mineralisation are mediated by biological processes, but its availability also depends on water, temperature, and other soil and environmental characteristics (Rieke et al., 2022). Soil biological community is influenced by soil organic matter (SOM) and structural habitat, affecting soil fertility, plant nutrient uptake and growth (Clapperton et al., 2007). Moreover, nitrogen deposition increases organic carbon storage through higher production of plant biomass, and therefore higher carbon is returned to the soil (Tang et al., 2023).

Nitrogen is continuously supplied to cultivated plants through fixation from the air by legumes, fertilisation with mineral fertilisers and green and animal manure, in addition to that available in the soil nutrient pool. Industrial cropping heavily depends on mineral fertiliser to sustain crop production. However, due to its high mobility, nitrogen is easily leaked or emitted to the environment and is a major contributor to water and air pollution (Chataut et al., 2023; Ramakrishnan and Ghaly, 2015), causing eutrophication, soil acidification, water pollution and greenhouse gas emissions. There is an urgent need to reduce N inputs and increase use efficiency (Billen et al., 2021).

Enhancing soil biodiversity that sustains nutrient cycling and ES are fundamental to reduce reliance on mineral fertilisers. Soil biota needs suitable habitats to thrive and develop to consequently provide ecosystem functions such as decomposition, mineralisation etc. (Martin and Sprunger, 2021; Scavo et al., 2022). Annual management practices to enhance soil fertility include legume intercropping, organic amendments and green manure (Duchene et al., 2017; Maeder et al., 2002). Cover crops before the main crop reduce leaching and improve nutrient use efficiency (Scavo et al., 2022). Rotating different crops can reduce the reliance on external inputs (MacLaren et al., 2022; M. E. Smith et al., 2023). While the underpinning mechanisms remain unclear, in the long run, cover crops, crop rotation and perennials, contribute to increasing SOM and plant nutrient capture (Ma et al., 2023; Zani et al., 2023).

3. Conceptualisation of the crop production function

Building on the ecology of the cropping system (Section 2), we introduce the economic perspective of managing for crop yield at the field-scale utilising a combination of anthropogenic inputs, such as plant protective products, fertiliser and mechanical measures, and ES. We assume that all combinations of reliance on anthropogenic inputs and ES are possible, i.e., we depict a continuum of potential farming strategies at the field-scale Farmers can choose mixtures of anthropogenic and ES-based strategies, which are highly likely to occur in reality (Höglind et al., 2021). The model is designed to fit the scale of the field, which is commensurate to that of crop ecosystem processes, and for a crop not requiring animal-mediated pollination. We depict an annual snapshot, determining the effects of current management, biodiversity based ES, farmers' skills and biogeophysical context on the output. The model considers the direct economic and ecological factors determining crop yield. Factors related to legislative, financial and social institutions are outside of the scope as they only indirectly impact crop yields by defining the feasibility of specific management practices. Similarly, negative externalities that extend beyond the field scale, such as adverse health effects or eutrophication of water bodies due to leaching, are not included.

3.1. Introducing ES to production functions for cropping systems

We depart from a standard production function model for yield based on labour, capital, and intermediate inputs as the basis to describe management practices (Coelli et al., 2005) and extend it to incorporate the relationships between ES and anthropogenic management, i.e., plant protective products, fertiliser, and fuel. This allows us to disentangle the capital, labour, and input requirements for input-intensive and ES-based strategies (see Fig. 2).

We differentiate between three components determining the final crop yield at the field scale: a fixed component, the deterministic component affected by management, and a stochastic component (Fig. 2). First, the system's overall yield potential is set by the farmer's characteristics, such as age, experience, human capital, and attitudes, as well as a biogeophysical potential yield, representing the maximum attainable yield given by biophysical factors like solar radiation, temperature, atmospheric CO_2, and crop genetic material, which are location-specific but theoretically independent of soil properties under the assumption that adequate water and nutrients can be managed (van Ittersum et al., 2013). This theoretical yield is achieved in the absence of water and nutrient limitations and biotic stress, with sowing dates, planting density, and cultivar ideal for the local conditions (van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997). The field and farmer parameters are considered fixed, as the farmer lacks the ability to change them within the model's temporal and spatial scope.

Second, the deterministic component captures factors that the farmer can alter through management, i.e., the use of labour, physical capital and intermediate inputs. Based on the main compartments and actors involved in a cropping system (Fig. 1), we consider three production inputs of crop yield: (1) net weed control f_{WC}, (2) net pest control f_{PC}, and (3) net soil fertility f_F. We define these as production factors in an aggregate production function for the field, assuming that the crop in question does not require animal-mediated pollination. Land is omitted as a direct input as we consider yield on a per land unit basis. The choice of production factors is coherent with comparable empirical estimations based on marketable inputs such as herbicides, insecticides, fungicides and fertilisers (Gardebroek et al., 2010) and ecological models (Bommarco et al., 2013; Duru et al., 2015).

Typical crop production functions are based on human-made inputs (Antle and Capalbo, 2001; Gardebroek et al., 2010; Lichtenberg and Zilberman, 1986). Since crop production is inevitably relying on ES, we highlight in our model how anthropogenic inputs and ES can complement and substitute each other. The production factors f_{WC}, f_{PC} and f_P make up a net service composed of contributions of anthropogenic inputs and biodiversity. In other words, they aggregate combinations of agrochemical inputs, mechanical measures and ES provided through intermediate inputs (I), labour (L), and physical capital (K) (Fig. 2). For simplicity, we treat the ES supporting weed control, pest control and soil fertility as independent despite the existence of interdependencies among various functions. For instance, organisms can perform multiple functions, thereby providing several services, or they can impact functions through predation or by otherwise influencing other organisms. Additionally, chemical inputs and mechanical practices often impact the provisioning of more than one production factor.

Last, and similar to farmer characteristics and potential yield, the stochastic component represent aspects outside the influence of the farmer, i.e., that cannot be managed. It contains random detrimental fluctuations of growing conditions, e.g., through weather shocks. Our focus is on the deterministic component, which can – at least partially – be managed in the short-term.

3.2. General production function for cropping systems

We assume that the cropping system is at a near stable state, in which only small changes occur over time. This implies that certain manage-

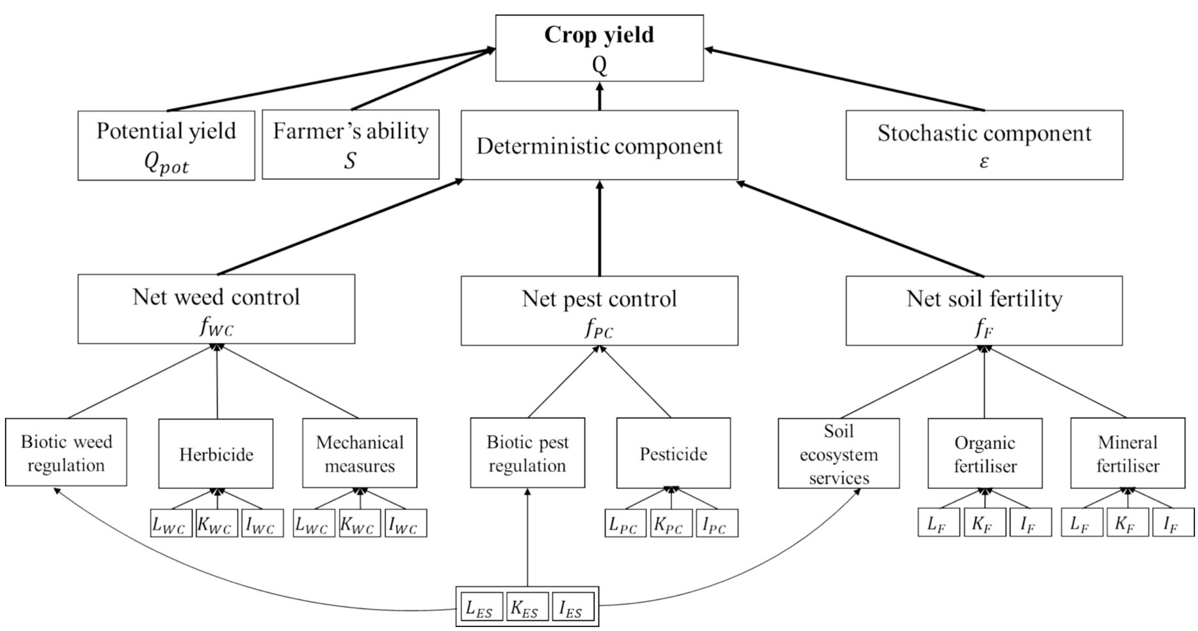

Fig. 2. Cascade diagram of the aggregate production function and the sub-functions of the production factors provided through management (labour L, physical capital K, and intermediate inputs I). Net services (i.e., weed control, pest control and soil fertility) are provided by a combination of ecosystem services (i.e., biotic weed regulation, biotic pest regulation, and soil ecosystem services) and anthropogenic inputs (i.e., herbicide application or mechanical weed control, pesticide applications, and organic and mineral fertiliser applications). Both forms of management require labour, physical capital (i.e., machinery and other equipment) and intermediate inputs (e.g., herbicides, pesticides, fertilisers, fuel or seeds for non-crop plants).

ment practices (e.g., high- or low-input management) have been predominant for a substantial time period. The static setup of the model is justified because the ecological evolution of a cropping system — both towards high biodiversity and soil health as well as towards low biodiversity and depleted soils — can take several years to decades, at least for some processes (Marini et al., 2020; M. E. Smith et al., 2023). Moreover, farmers' decision making tends to be short term focused, i.e., management practices are based on the status quo and disregard consequences in terms of ES and disservices (Tilman et al., 2002). The proposed model spans over a field and a growing season from initial preparations, sowing, and treatments to harvest. We conceptualise the dependence of yield Q (ton/ha) on weed control f_{WC}, pest control f_{PC}, and soil fertility f_F at the aggregate level as:

$$Q = Q_{pot}*S*f(f_{WC}, f_{PC}, f_F) - \varepsilon \quad Q \in [0, Q_{pot}] \tag{1}$$

Q_{pot}, the potential yield (ton/ha), and S, the farmer characteristic, together define the theoretical maximum of production. If $S<1$, the biogeophysical potential yield cannot be realised. We assume that farmer characteristics S such as skills, education, experience, motivation, etc. are provided as yearly endowments. The actual yield is further mediated by a net service function f nesting f_{WC}, f_{PC}, and f_F, i.e., the functions representing the net weed control, pest control, and soil fertility, forming the deterministic component. They are defined between zero and one. ε captures the stochastic component, causing negative variation in the yield compared to that set by biogeophysical constraints, farmer characteristics and management.

The potential yield, Q_{pot}, is the absolute maximum output in the production function, thus defining the production frontier. Inefficiency, i.e., production under the frontier, occurs when farmer characteristics, the net service function $f(f_{WC}, f_{PC}, f_F)$, or the weather conditions are suboptimal. f_{WC}, f_{PC} and f_F are limiting, i.e., unless in optimum, only a fraction of the potential yield can be reached. They are expressed positively, i.e., as control instead of damage functions, as dimensionless levels of service provided. The production factors can be provided through inputs and ES. For a discussion on possible functional forms of eq. (1) see Appendix A. For an overview of variables, units, domains, and scales see Table 1.

The dimensionless factor farmer characteristics S, ranging from 0 to 1, includes socioeconomic traits and human capital, i.e., the accumulation of skills, qualifications, and individual characteristics, which is strongly related to firm-level performance (Crook et al., 2011). Ability and skills have an important impact on productivity and efficiency outcomes of production (Hoang-Khac et al., 2022). Since the build-up of knowledge and skills is a long-term process, S is considered a parameter beyond the control of the farmer in the short-term.

3.3. Functions for the net services weed control, pest control, and soil fertility

We introduce separate production functions for weed control f_{WC}, pest control f_{PC}, and soil fertility f_F, to disentangle labour-, capital-, and input demands for each production factor. For an overview of variables, units, domains, and scales see Table 2. Eqs. (2.1)–(2.2) describe f_{WC}, f_{PC}, and f_F as functions of corrective management M^c_{WC}, M^c_{PC}, and M^c_F, and by ES ES_{WC}, ES_{PC}, and ES_F.

$$f_{WC} = f\left(M^c_{WC}, ES_{WC}\left(B_{WC}\left(M^p_{WC}, M^c_{WC}\right)\right), \epsilon_{WC}\right) \tag{2.1}$$

$$f_{PC} = f\left(M^c_{PC}, ES_{PC}\left(B_{PC}\left(M^p_{PC}, M^c_{PC}\right)\right), \epsilon_{PC}\right) \tag{2.2}$$

$$f_F = f\left(M^c_F, ES_F\left(B_F\left(M^p_F, M^c_F\right)\right), \epsilon_F\right) \tag{2.3}$$

Corrective management measures rely on anthropogenic inputs of labour, capital, agrochemicals (Fig. 2). The ES ES_{WC}, ES_{PC}, and ES_F are functions of the relevant biodiversity for the respective service, B_{WC}, B_{PC}, and B_F, which in turn depends on both corrective and preventative management actions M^p_{WC} , M^p_{PC} and M^p_F. Preventative management entails ES-based management, such as the provisioning of habitat and resources for predators supporting the control of pest populations (Crowder et al., 2010) or adapting the management of the cropping system to reduce germination of weeds from the seedbank and improve crop competitiveness (Hawes et al., 2021).

All production factors also have negative stochastic variations, ϵ_{WC}, ϵ_{PC}, and ϵ_F, beyond the farmers' control. They can include phenomena like the introduction of new weeds, beneficial conditions for pests, or nutrient leaching and soil erosion due to heavy rains.

3.4. Management inputs

Corrective and preventive management require specific combinations of inputs. While intermediate inputs, i.e., goods that are used as inputs in the production process to create other goods, are rather associated with corrective management (e.g., herbicides, pesticides, mineral fertiliser), some ES-service based management can also require inputs such as non-crop seeds. Eqs. (2.1)–(2.3) are expanded to make explicit the roles of the management inputs:

Table 1
Overview of units, domain, and observational unit of the variables in the general production function (1).

Variable	Unit	Domain of definition	Scale/Observational unit
Actual yield Q	ton/ha	$[0, Q_{pot}]$	Field
Potential yield Q_{pot}	ton/ha	$[0, Q_{pot}]$	Field
Ability S	Dimensionless	[0,1]	Farm
Weed control f_{WC}	Dimensionless	[0, 1]	Field
Pest control f_{PC}	Dimensionless	[0, 1]	Field
Soil fertility f_F	Dimensionless	[0, 1]	Field
Stochastic term ε	ton/ha	$[-Q_{pot}, 0]$	Field

Table 2
Overview over units, domain, and observational unit of the variables in the production functions for weed control, pest control, and soil fertility (1).

Variable	Unit	Domain of definition	Scale/ Observational unit
Level of weed control, pest control, soil fertility f_{WC}, f_{PC}, f_F	Dimensionless	[0,1]	Field
Corrective management M^c_{WC}, M^c_{PC}, M^c_{PC}	Dimensionless	[0, ∞]	Field
Preventative management M^p_{WC}, M^p_{PC}, M^p_{PC}	Dimensionless	[0,1]	Field
Preventative annual management M^a_{WC}, M^a_{PC}, M^a_{PC}	Dimensionless	[0,1]	Field
Preventative long-term management M^r_{WC}, M^r_{PC}, M^r_{PC}	Dimensionless	[0,1]	Field
Ecosystem service ES_{WC}, ES_{PC}, ES_F	Dimensionless	[0,1]	Field
Relevant biodiversity B_{WC}, B_{PC}, B_F	Number of functional groups	[0,∞]	Field
Labour L	Labour inputs	[0,∞]	Field
Capital K	Capital inputs	[0,∞]	Field
Intermediate inputs I	Quantities of inputs	[0,∞]	Field
Efficiency parameters α^c_{WC}, α^c_{PC}, α^c_F, α^a_{WC}, α^a_{PC}, α^a_F and α^r_{WC}, α^r_{PC}, α^r_F	Dimensionless	[0,1]	Field
Stochastic terms ϵ_{WC}, ϵ_{PC}, ϵ_F	ton/ha	[−1,0]	Field

$$f_{WC} = f\left(M^{c}_{WC}(L_{WC}, K_{WC}, I_{WC}), ES_{WC}\left(B_{WC}\left(M^{p}_{WC}(L_{ES}, K_{ES}, I_{ES}), M^{c}_{WC}(L_{WC}, K_{WC}, I_{WC})\right)\right), \epsilon_{WC}\right) \tag{3.1}$$

$$f_{PC} = f\left(M^{c}_{PC}(L_{PC}, K_{PC}, I_{PC}), ES_{PC}\left(B_{PC}\left(M^{p}_{PC}(L_{ES}, K_{ES}, I_{ES}), M^{c}_{PC}(L_{PC}, K_{PC}, I_{PC})\right)\right), \epsilon_{PC}\right) \tag{3.2}$$

$$f_{F} = f\left(M^{c}_{F}(L_{F}, K_{F}, I_{F}), ES_{F}\left(B_{F}\left(M^{p}_{F}(L_{ES}, K_{ES}, I_{ES}), M^{c}_{F}(L_{F}, K_{F}, I_{F})\right)\right), \epsilon_{F}\right) \tag{3.3}$$

While corrective management is often targeted to one particular service (e.g., herbicide applications to eradicate weeds), preventative management is broader and can impact several ES (e.g., crop rotations to prevent competitive weeds and improve soil fertility).

3.5. Annual vs. long-term preventative management

Describing corrective, input-dependent management is rather straightforward. Intermediate inputs (I) such as herbicides, pesticides, and mineral fertiliser are applied using labour (L), and physical capital (K) to reach a target. This aspect of field treatment is typically considered in production functions to determine optimal application levels (Gardebroek et al., 2010; J. W. Jones et al., 2017; Lichtenberg and Zilberman, 1986).

Preventative biodiversity-based management acts at two time scales. There are shorter-term measures, M^a, that farmers can implement each year, such as planting cover crops, suspending pesticide applications, minimising tillage, or establishing annual flower strips. Conversely, other practices, denoted by M^r, require consistency over several years-due to a slower effect build-up, although we consider here only the management inputs relative to the current period. Examples of these practices are functionally diversifying crop rotations, intercropping, or perennial field margins. The two types of M^p are explicitly differentiated in the model:

$$ES_{WC} = f\left[B_{WC}\left(M^{p}_{WC}\left(M^{a}_{WC}(L_{ES}, K_{ES}, I_{ES}), M^{r}_{WC}(L_{ES}, K_{ES}, I_{ES})\right)\right), M^{c}_{WC}(L_{WC}, K_{WC}, I_{WC})\right] \tag{4.1}$$

$$ES_{PC} = f\left[B_{WC}\left(M^{p}_{PC}\left(M^{a}_{PC}(L_{ES}, K_{ES}, I_{ES}), M^{r}_{PC}(L_{ES}, K_{ES}, I_{ES})\right)\right), M^{c}_{PC}(L_{PC}, K_{PC}, I_{PC})\right] \tag{4.2}$$

$$ES_{F} = f\left[B_{F}\left(M^{p}_{F}\left(M^{a}_{F}(L_{ES}, K_{ES}, I_{ES}), M^{r}_{F}(L_{ES}, K_{ES}, I_{ES})\right)\right), M^{c}_{F}(L_{F}, K_{F}, I_{F})\right] \tag{4.3}$$

3.6. Effectiveness of management practices

Management determines the potential of the system through legacy effects, which have been built up over decades and impact the effectiveness α of current measures. We introduce an additional coefficient mediating effectiveness in order to account for the management history, linking to the assumption that a management has been predominant for several years, the otherwise static setting. Acknowledging that the same management practices can have varying effectiveness depending on previous strategies, we obtain

$$f_{WC} = f\left(M^{c}_{WC}(\alpha^{c}_{WC}), ES_{WC}\left(B_{WC}\left(M^{p}_{WC}\left(M^{a}_{WC}(\alpha^{a}_{WC}), M^{r}_{WC}(\alpha^{r}_{WC})\right), M^{c}_{WC}(\alpha^{c}_{WC})\right)\right), \epsilon_{WC}\right) \tag{5.1}$$

$$f_{PC} = f\left(M^{c}_{PC}(\alpha^{c}_{PC}), ES_{PC}\left(B_{WC}\left(M^{p}_{PC}\left(M^{a}_{PC}(\alpha^{a}_{PC}), M^{r}_{PC}(\alpha^{r}_{PC})\right), M^{c}_{PC}(\alpha^{c}_{PC})\right)\right), \epsilon_{PC}\right) \tag{5.2}$$

$$f_{F} = f\left(M^{c}_{F}(\alpha^{c}_{F}), ES_{F}\left(B_{F}\left(M^{p}_{F}\left(M^{a}_{F}(\alpha^{a}_{F}), M^{r}_{F}(\alpha^{r}_{F})\right), M^{c}_{F}(\alpha^{c}_{F})\right)\right), \epsilon_{F}\right) \tag{5.3}$$

The effectivity parameters α^{c}_{WC}, α^{c}_{PC}, α^{c}_{F}, for corrective, α^{a}_{WC}, α^{a}_{PC}, $\alpha^{a}_{F,}$ for annual preventative and α^{r}_{WC}, α^{r}_{PC}, $\alpha^{r}_{F,}$ for long-term preventative management are aggregates of the previous years' management. The farmer cannot influence them in the current period. Hence, they are treated as constants in the short term. For a discussion on the long-term evolvement of the parameters see Appendix B. These parameters are defined between zero and one and mediate the effect of the current period's management. The effectiveness parameters enable a comparison between different fields where inputs and ES can have, ceteris paribus, different impacts on yield.

In summary, we identified five determinants of the net level of weed control, pest control, and soil fertility: (i) corrective management, which is input intensive, (ii) ES, which can be managed through preventative management and degraded through corrective management, (iii) the efficiency of a management strategy, which has been built up through past management, (iv) stochastic fluctuations in the level of ES provisioning, which are beyond the farmers control, and (v) labour, capital, and intermediate inputs, which are necessary for each management practice. Once combined, the weed control, pest control, and soil fertility functions depend on these determinants as

Table 3
Overview over possible economic indicators.

Economic input	Variable in the model	Ideal measurement	More feasible indicator	Secondary data
Labour	L			
		Total hours of unpaid and paid labour, and skill level of work hours at the field scale including a description of the specific practices labour was allocated for	Total hours of unpaid and paid labour, and skill level of work hours at the field scale Approximation of work hours allocated to specific practices has to be done based on intermediate input use (i.e., work required for spraying) or machine use (i.e., work required for using the plow)	Total number/h of full time equivalent (FTE) labour from farm accounting data, i.e., hours are aggregated at farm level, ideally including family labour Alternative: cost of labour Labour hours must be scaled down to the field level and approximation of work hours allocated to specific practices has to be done based on intermediate input use (i.e., work required for spraying) or machine use (i.e., work required for using the plow)
Example		For weed control only: Böcker et al. (2019): Field-level data from the Swiss Central Evaluation of Agri-environmental Indicators of the Agroscope Research Station 2009–2013 for 108 farms		Carpentier and Letort (2014): Farm Accountancy Data Network (FADN), number of annual workers Tiedemann and Latacz-Lohmann (2013): Farm accounting data for the financial years 1999 / 2000–2006 / 2007, for a balanced panel of 37 organic arable farms and a conventional farming reference group (n = 37) Zhengfei et al. (2006): Panel data from the Dutch Agricultural Economics Research Institute 1425 observations from 323 farms, quality-corrected man-years and included family labour, labour share per crop- calculated based on expert assessment Kumbhakar et al. (2014): Norwegian Farm Accountancy Survey collected by the Norwegian Agricultural Economics Research Institute (NILF), n = 1000 grain farms; labor hours used on the farm, measured as total number of hours worked, including management, family and hired workers Lyson and Welsh (1993): (Country-level) census of agriculture data from 1978, 1982, and 1987 Koiry and Huang (2023): unbalanced panel data from the Farm Accounting Data Network (FADN) for the period 2010–2016
Capital	K			
		Total used hours of assets in ownership and total used hours of rented physical assets at the field scale including a description of the specific practices labour was allocated for	Total used hours of assets in ownership and total used hours of rented physical assets at the farm scale	Total value/costs of assets in ownership based on farm accounting data and cost of rented physical assets aggregated at farm level: Implicit use of physical assets (i.e., dividing the total costs of assets by their respective price indices)
Example		For weed control only: Böcker et al. (2019): Field-level data from the Swiss Central Evaluation of Agri-environmental Indicators of the Agroscope Research Station 2009–2013 for 108 farms	Carpentier and Letort (2014): Farm Accountancy Data Network (FADN), physical capital on farms (buildings, machinery)	Gardebroek et al. (2010): Dutch farms included in the farm accounting system of the Dutch Agricultural Economics Research Institute (LEI) Lyson and Welsh (1993): (Country-level) census of agriculture data from 1978, 1982, and 1987

(*continued on next page*)

Table 3 (*continued*)

Economic input	Variable in the model	Ideal measurement	More feasible indicator	Secondary data
				Tiedemann and Latacz-Lohmann (2013): Farm accounting data for the financial years 1999 / 2000–2006/ 2007, for a balanced panel of 37 organic arable farms and a conventional farming reference group (n = 37) Koiry and Huang (2023): unbalanced panel data from the Farm Accounting Data Network (FADN) for the period 2010–2016 Zhengfei et al. (2006): Panel data from the Dutch Agricultural Economics Research Institute 1425 observations from 323 farms, capital stock aggregated over machinery, equipment, and buildings, aggregated over the replacement values, instead of the services Kumbhakar et al. (2014): Norwegian Farm Accountancy Survey collected by the Norwegian Agricultural Economics Research Institute (NILF), n = 1000 grain farms; farm fixed and capital costs
Intermediate inputs	*I*			
		Total amount and type of intermediate inputs at the field scale	Total amount of intermediate inputs based on farm accounting data, i.e., inputs aggregated at farm level:	Total cost of aggregate intermediate inputs based on farm accounting data: Implicit volumes, i.e., dividing the total costs of inputs by their respective price indices
Example		Brady et al. (2015): Long-term experiments in Sweden (n = 485), Germany (n = 84), Denmark (n = 144), and Oregon (n = 558) For some chemical and fuel inputs for weed control only: Böcker et al. (2019): Field-level data from the Swiss Central Evaluation of Agri-environmental Indicators of the Agroscope Research Station 2009–2013 for 108 farms		Gardebroek et al. (2010): Dutch farms included in the farm accounting system of the Dutch Agricultural Economics Research Institute (LEI) Carpentier and Letort (2014): Farm Accountancy Data Network (FADN) Tiedemann and Latacz-Lohmann (2013): Farm accounting data for the financial years 1999 / 2000–2006 / 2007, for a balanced panel of 37 organic arable farms and a conventional farming reference group (n = 37) Finger (2014): Swiss farm accountancy data network (FADN) data of 193 and 327 farms with intensive and low-input wheat production Zhengfei et al. (2006): Panel data from the Dutch Agricultural Economics Research Institute 1425 observations from 323 farms Kumbhakar et al. (2014): Norwegian Farm Accountancy Survey collected by the Norwegian Agricultural Economics Research Institute (NILF), n = 1000 grain farms; variable farm inputs, measured by variable costs

$$f_{WC} = f\left(M^{c}_{WC}\left(L_{WC}, K_{WC}, I_{WC}, \alpha^{c}_{WC}\right), ES_{WC}\left(B_{WC}\left(M^{p}_{WC}\left(M^{a}_{WC}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{a}_{WC}\right), M^{r}_{WC}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{r}_{WC}\right)\right), M^{c}_{WC}\left(L_{WC}, K_{WC}, I_{WC}, \alpha^{c}_{WC}\right)\right)\right), \epsilon_{WC}\right) \tag{6.1}$$

$$f_{WC}\ \epsilon\ [0,1]$$

$$f_{PC} = f\left(M^{c}_{PC}\left(L_{PC}, K_{PC}, I_{PC}, \alpha^{c}_{PC}\right), ES_{PC}\left(B_{PC}\left(M^{p}_{PC}\left(M^{a}_{PC}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{a}_{PC}\right), M^{r}_{PC}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{r}_{PC}\right)\right), M^{c}_{PC}\left(L_{PC}, K_{PC}, I_{PC}, \alpha^{c}_{PC}\right)\right)\right), \epsilon_{PC}\right) \tag{6.2}$$

$$f_{PC}\ \epsilon\ [0,1]$$

$$f_{F} = f\left(M^{c}_{F}\left(L_{F}, K_{F}, I_{F}, \alpha^{c}_{F}\right), ES_{F}\left(B_{F}\left(M^{p}_{F}\left(M^{a}_{F}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{a}_{F}\right), M^{r}_{F}\left(L_{ES}, K_{ES}, I_{ES}, \alpha^{r}_{F}\right)\right), M^{c}_{F}\left(L_{F}, K_{F}, I_{F}, \alpha^{c}_{F}\right)\right)\right), \epsilon_{F}\right) \tag{6.3}$$

$$f_{PC}\ \epsilon\ [0,1]$$

For a discussion on possible functional forms of eq. (1) and eqs. (7.1)–(7.3) see Appendix A. For an overview of variables, units, domains, and scales see Table 2.

4. Indicators to assess the structural crop production function

Ecological and economic estimates are needed to operationalise the production function. However, most variables are either impossible or too costly to measure directly, calling for indicators that are practical while still reasonable to handle the complexity and multifaceted nature of the variables in the production function (Pannell and Schilizzi, 1999). In Tables 3, and 4 we present an overview of indicators for anthropogenic management, net services, biodiversity and ecosystem services. We first introduce an ideal measurement, i.e., the variable corresponding to or closest to the described component in the production function but that most often cannot be measured directly. We then present proxy

Table 4

Overview of possible ideal measurements and feasible indicators of net services (f) weed control (WC), pest control (PC) and soil fertility (F), and examples of ecosystem services (ES) and biodiversity components (B) linked to each net service. All are assumed to be measured representatively at the field scale. Examples with literature reference provide insights on the state of the art.

Factor	Model variable	Ideal measurement	More feasible indicators	Example references for feasible indicators
Weed control (WC)				
Net weed control	f_{WC}	Actual weed competitiveness with crop	Weed biomass Weed relative abundance Weed growth	(Hofmeijer et al., 2021; Milberg and Hallgren, 2004; Storkey and Neve, 2018)
Relevant biodiversity	B_{WC}	Actual community composition of weeds and weed predators	Weed seedbank Seed predator community composition	(Lami et al., 2023)
Ecosystem service	ES_{WC}	Actual regulation of weed populations	Seed predation estimates	(Daouti et al., 2022)
Pest control (PC)				
Net pest control	f_{PC}	Actual yield loss due to pest infestation	Pest incidence Pest and predator densities Crop damage by pests	(Tschumi et al., 2015)
Relevant biodiversity	B_{PC}	Actual community composition of all predators, parasitoids and antagonists to herbivorous pests	Arthropod predator community composition Herbivore community composition	(Aguilera et al., 2020)
Ecosystem service	ES_{PC}	Actual regulation of pest populations	Predation rate estimates Pest population change in time	(Boetzl et al., 2020; Thies et al., 2011)
Soil fertility (F)				
Net soil fertility	f_F	Plant available nitrogen across the season	Mineralised nitrogen Soil organic matter (SOM) Soil organic carbon (SOC)	(Schindelbeck et al., 2016; Whalen et al., 2022; Wiesmeier et al., 2019)
Soil biodiversity	B_F	Actual functional composition of the soil biome	Microbial activity Microbial diversity Soil fauna communities	(Brussaard et al., 2007; Tiemann et al., 2015)
Ecosystem service	ES_F	Actual flows and stocks of all forms of nitrogen	Decomposition rate Soil mineral nitrogen pools Nitrogen fixation Nitrogen leaching Greenhouse gas emission potential	(Keuskamp et al., 2013)

indicators that are feasible to estimate, correlate with the ideal economic and ecological measurements, and are sometimes also available in data bases (Antle, 2011).

4.1. Indicators for labour, capital, and intermediate inputs

The economic variables required describe the production inputs, typically defined in terms of labour, capital, and intermediate inputs (Coelli et al., 2005), and their scale, i.e., farm vs. field (Fig. 2, bottom; Table 3). These variables are lacking at the field scale but are often well documented in national and EU-wide data bases at firm-aggregate level through their bookkeeping (e.g., FADN(European Commission. Directorate-General for Agriculture and Rural Development, 2019)). Hence, an approach to scale down variables is needed to avoid scale mismatches with ecological data and match the scale of production. An example is using a standard linear regression model to disaggregate costs for the whole farm into costs per hectare for each crop (Jacquet et al., 2011).

Common measures of labour inputs, denoted by L in our model, are number of persons employed, number of full-time equivalent employees (FTEs), total wages, and number of hours (Coelli et al., 2005). In addition to these standard measures of labour inputs, information on the worker skill level is essential to explain differences in productivity, since a worker's role in the production process involves both their physical effort and the contributions of their human capital. Human capital is often measured in terms of the type and level of education of the workers or the firm manager, the number of years of work experience and/or age (Baldos et al., 2019; Nilsson et al., 2022). Being difficult to quantify, human capital is captured as an overall potential, S (see eq. (1)). While quantitative data on labour hours is often available through secondary sources, i.e., register data, it is often unclear how many hours are allocated to specific practices such as weed control, pest control or enhancing soil fertility. Some of the labour allocation, particularly corrective management practices, can be estimated by combining labour with data on intermediate inputs and capital use estimating the labour demand of practices, e.g., by using the typical speed of a machine as an indicator.

Capital inputs in production, K in our model, are, unlike labour or intermediate inputs, not fully utilised or consumed within one accounting period and are considered durable (Coelli et al., 2005). Hence, their use in one period is a share of their lifetime, which is often calculated as depreciation rate, i.e., the gradual decrease in the value over time due to wear and tear, obsolescence, or aging. If the capital is not rented but owned, no market transaction is recorded when the physical assets are used as inputs in production and there is usually no record of the flow of productive services from the cumulative stock of past investments. Capital services can be measured as the service input per time unit (e.g., machine hours), while differentiating qualitatively different items of tangible capital (Shepherd, 2015).

Intermediate inputs, I in our model, are measured by type and quantity. Also non-marketed inputs such as manure from livestock production should be accounted for as it is technologically incorrect to exclude them from the input vectors (Shepherd, 2015). Farmers often document labour hours, machine hours (and consequently fuel needs), as well as inputs in farm management software programmes. A challenge is to avoid double accounting when assigning a specific task to just one production factor. For instance, tillage can be classified as weed management by uprooting weeds, and disrupting their growth, but also as soil fertility when incorporating organic matter such as crop residues, compost, or manure.

4.2. Indicators for net services, biodiversity and ecosystem services

While for economic indicators it is often possible to separate the inputs and their effects, ecological indicators inherently revolve around the net services (f_{WC}, f_{PC} and f_F in Fig. 2), i.e., characterise the net results of synergies and trade-offs between ecological processes, anthropogenic inputs and mechanical measures (see Table 4).

The variables of the general production function range between 0 and 1 (Eq. (1), Table 1). In the case of weed and pest control, perfect control ($f_{WC} = 1$ and $f_{PC} = 1$) would translate to a net result of weeds and pests below critical thresholds. A soil fertility with the value 1 provides nutrients such that plant growth is not hampered.

Weed control, f_{WC}, aims at reducing wild plants emergence, thereby minimising yield losses attributed to weeds. The ideal measurement of the net level of weed control would involve quantifying the total number of weeds emerging in the field and their competitiveness with the crop, considering all management practices implemented by the farmer and its context. A more feasible indicator of weed control is weed richness and relative abundance in representative parcels of a field. A more diverse community can be composed by more or less acceptable weeds (higher/lower weediness) (Connolly et al., 2018; Milberg and Hallgren, 2004) and can promote higher predator biodiversity (Schumacher et al., 2020). Weed biomass can also be an adequate indicator of weed control because the higher the biomass, the higher the damage or competitiveness of the weeds (Armengot et al., 2016). Examining the seed bank provides insights into the expected weed infestation in the future. This supports proactive weed management strategies and selecting appropriate practices, such amount of pesticide, specific active compounds or annual managements (Petit et al., 2015).

Pest control, f_{PC}, reduces pests feeding on the crop. The ideal measurement of effectiveness of pest control is the total number of pests directly affecting the crop at any growth stage. However, obtaining precise total pest numbers is impossible. Instead, indicators such as pest densities and relative numbers from smaller field plots are utilised, which can then be spatially extrapolated to assess overall pest pressure to the unit of interest (Schipanski et al., 2014). Additionally, inflicted crop damage can be employed as an indicator for (the success of) pest control. Another indirect indicator is predator count at a certain time. Higher densities of predators, especially those exhibiting specific species preference or traits can imply a biological regulation keeping pest populations below economic thresholds (Sexton et al., 2007; Stern, 1973).

Soil fertility f_F, sustains plant growth through nutrient supply. Its ideal measurement, mirroring the effects of all classes of management together, would be the plant available nitrogen, i.e., mainly in the form of nitrate, available at any moment in the field. Fields are usually heterogeneous in soil composition and characteristics, therefore nutrients are generally unevenly distributed. Most common feasible indicators that relate to our definition of soil fertility can include decomposition rates, soil organic matter, carbon content, and total available nitrogen levels (Bradford et al., 2016; Brady et al., 2015; Bünemann et al., 2018). Soil biodiversity supports a range of functions in the soil and components and holds potential to indicate ES (Bender et al., 2016; Kuypers et al., 2018). Soil health is a broader concept that can be assessed for instance using the CASH manual (Schindelbeck et al., 2016).

Biodiversity – the basis for ES provisioning – is commonly described in terms of species richness, species abundance and biomass (Jacobsen et al., 2019; Krey et al., 2021; Snyder, 2019). Diversity of functional groups, such as groups of predators with different body sizes, feeding or habitat preferences, behaviours etc., often better reflect the ability of a community to deliver functions in cropping systems (Gagic et al., 2015; Gerlach et al., 2013). A management practice can either influence the net services weed control, pest control or soil fertility directly or indirectly through impacting biodiversity. Practices with a direct effect on net services, e.g., synthetic herbicides and pesticides, can have negative side effects on biodiversity.

5. Discussion

We provide a structural crop production function to model the contribution of ES provided by biodiversity as input in agricultural production. In particular, we present a model structure for productivity analysis of inputs quantifying contributions of anthropogenic inputs (e.g., pesticides and fertilisers) and ES (e.g., biotic weed and pest regulation, and soil ES) to crop production. The focus on productivity instead of profitability aligns with the objectives of integrating ecological preconditions in the economic understanding of crop production without a distortion by market prices. Our premise and primary motivation for integrating ES into the production function is that there is no production (and hence no potential profit) without biodiversity and ES (IPBES, 2019). Additionally, profitability analysis constitutes a simplified assessment based on the suggested model as it circumvents the difficulties of assigning market values to ES. Instead of attempting to identify market values for ES using imperfect valuation methods (Harrison et al., 2018; Schröter et al., 2014), we suggest determining management values by explicitly accounting for farming practices that aim at enhancing and utilising ES. The associate inputs can easily be quantified through the market prices for labour, capital and intermediate inputs, as a measure for the cost of ES.

With the model and indicators developed here we extend the conventional agricultural production functions for crop production to accommodate the main biophysical preconditions for crop production, i.e., pest control, weed control, and soil fertility instead of focusing on each service in isolation. Importantly, we make explicit and provide a tool to quantify the contribution of biodiversity and ES to crop production. In a production framework, the value of any asset is derived from the discounted flow of services it provides over time. Thus, considering ES in economic analysis provides information about the value of the underlying assets, in our case biodiversity, and the efficiency with which they are utilised (Hanley and Perrings, 2019). According to Hotelling's principle, the decision to conserve biodiversity and manage for ES depends on their relative value compared to other assets such as the effectiveness of anthropogenic inputs (Hotelling, 1931). Hence, if ES are not properly valued or considered unimportant to production, rational decision making in terms of yield maximising is impossible, and biodiversity conservation will solely depend on intrinsic, non-use values. Our model facilitates the inclusion of biodiversity and ES as production input and emphasises their importance and contribution to economic welfare (Rist et al., 2014).

Currently, the model captures management decisions on weed control, pest control and soil fertility. There are additional services at play for crop production, such as pollination and water availability, which increasingly rely on anthropogenic inputs, e.g., managed honeybees and irrigation. While these are not yet included in the framework, we have set up a structure such that these ES can be added with relative ease.

Our model allows for technological heterogeneity as well as heterogeneity in knowledge by the farmer. Unlike other approaches (Gardebroek et al., 2010), we do not depart from distinct production technologies for high- and low-input strategies. In either case, the basic requirements for crop production, weed control, pest control, and soil fertility, are the same – only their way of provisioning differs (Duru et al., 2015). Instead, our model accommodates different preferences for reliance on inputs or on ES. ES are omnipresent, however, the degree of care of and awareness for them differs. Even in intensively managed, highly input-dependent agricultural systems, ES are vital for crop production (Bommarco et al., 2013; Tittonell, 2014; Tscharntke et al., 2012). The proposed model supports explicit decision making on resource allocations, while allowing for a continuum of farming practices – from highly input-dependent to more ES- based crop production forms. Hence, our model is versatile and non-normative about different cropping practices. It allows to explore high-input farming as well as agroecological solutions. The latter aims to sustain yields by enhancing ES and thereby reducing the reliance on environmentally damaging inputs and technical solutions (Wezel et al., 2014).

Integrating ES into a production framework is of relevance for other sectors relying on biodiversity and ES, such as forestry, fisheries, biofuel production, or urban development and sustainable land use planning. While agricultural and resource economics, and economics in general, have traditionally focused on using marketed resources more efficiently and finding ways to price public goods and negative externalities as add-ons, our framework highlights that a more comprehensive integration of ES is possible within a production economic framework. Unaccounted non-marketed inputs such as ES can cause issues in econometric estimations of production, especially when they are observed by the decision maker, i.e., if the farmer is to some extent aware of ES and disservices. In this case, anthropogenic inputs (e.g., pesticides, fertiliser) are chosen as functions of latent factors, such ecosystem (dis)services (e.g., pest pressure, abundance of predators or soil health), which causes endogeneity problems (Ackerberg et al., 2015). Additionally, the combined effect of biodiversity and ES affects the efficiency of anthropogenic inputs, e.g., a more diverse weed community is less prone to resistance and responds more effectively to herbicide treatments (Storkey and Neve, 2018). In other words, the predictor variables (anthropogenic inputs) are correlated with ES, which are unobserved for the researcher when not explicitly accounted for and make up the error term. Simultaneously, ES are correlated to yield leading to biased estimates, i.e., an over- or underestimation of the effect of the anthropogenic input on yield.

Applying the model and exploring scenarios requires economic and ecological indicators of inputs and functions. We proposed indicators to empirically estimate the variables embedded in the model and provide examples on how to categorise management in corrective, and annual and long-term preventative management. However, better data is needed to enable economic-ecological integration and economic valuations of biodiversity contributions. Access to large data bases has advanced empirical economic research since the 1980s and it is now dominating the top journals (Angrist and Pischke, 2010; Einav and Levin, 2014; Hamermesh, 2013). However, certain crucial areas, including contributions of biodiversity and ES, remain neglected due the absence of "big data". Additionally, there is a mismatch in scales. While farm-level data is rather easily available for economic variables, field-level economic and ecological data is laborious to collect but necessary to connect with ecological information. Similarly, other relevant data, such as detailed information human capital, motivation and skills, are not found in register data.

The inclusion of biodiversity in economic research depends not only on data and integration in established frameworks such as production functions, but also on understanding the linkages among biodiversity, ES provisioning and management practices. The biodiversity-ecosystem function literature highlights both the feasibility of such research and its complexity (Garland et al., 2021; Hector and Bagchi, 2007; Wittwer et al., 2021). A deepened understanding of ecological mechanisms at the basis of ES can support the development of more refined or easier-to-estimate indicators. Interdisciplinary research requires utmost clarity to mitigate the compounding biases emerging in each engaged discipline, ensuring that they do not amplify each other. Our model and its combination with the suggested indicators aim at making the unmeasurable measurable, ultimately contributing to assign biodiversity conservation a similar weight as climate change mitigation.

Our model is static and assumes that a certain type of management practice has been predominant for a relevant period. Thus, judgements about productivity of inputs given the status quo and between field comparisons can be made based on the model. The model can provide a comparison in the effectiveness of ecosystem management compared to the effectiveness of anthropogenic inputs given the management history. The model could be further developed to include dynamics. This can for example facilitate the mapping of possible transition pathways towards more ES-based management. A dynamic model can also consider the change in time of effectiveness (see eq. (5.1)–(5.2)), for example as the result of building-up of pesticide resistances and changes in soil fertility. For a discussion on how the effectiveness parameters can evolve see Appendix B. Additionally, human capital, including education, skills, experience but also attitudes and motivations, can change in the long-run and thus become a control variable. Another interesting avenue for future research is to analyse how social and legal institutions (e.g., cooperatives, regulations) and financial institutions (investments, access to credits, subventions) influence choices of production sets. This could inform policy makers about the most effective instruments to encouraging ES-based management.

Biodiversity and the resulting ES can be characterised as a renewable resource, which can be exploited and collapse. Similar to a forest stand or a fish stock, our model is a starting point to characterise the state variables and control functions that capture agricultural activities to manage weeds, pests, and soil fertility. The development of the state variable can be expressed as a controlled differential equation. Methods of optimal control theory can be applied to characterise management optimising yields for each year within a long-term planning horizon while accounting for the change in the biophysical conditions. This is relevant for policy by considering that restoring biodiversity after a shift from input-intensive management takes time with potential yield losses during the transition (M. E. Smith et al., 2023). Our model can contribute to identifying behaviours that might appear economically rational, however, only when disregarding how fundamental ES are for agricultural production. In a state of substantial depletion of the ecosystem due to intensive management, the discounted flow of ES is close to zero and investments in ES-based management are economically irrational. However, when taking tipping-point dynamics and the crucial dependence on a certain level of biodiversity into consideration (Rist et al., 2014; Tscharntke et al., 2012), it becomes apparent that economic argumentation alone is insufficient. Ecological evidence suggests that production is nearly impossible or immensely cost intensive without the support of ES, which is supported by smaller-scale evidence of abandoned production sites due to local extinction and pollution (Partap et al., 2001; Partap and Ya, 2012). If the provisioning of biotic weed and pest regulation and soil health are close to zero, the provisioning of net services for weed control, pest control and soil health are nearly zero. Hence, there is not only a need to understand lock-in effects of intensive management due to technical and resistance-caused dependences (Bakker et al., 2020; Hu, 2020), but also to design policies facilitating the substitution of agrochemicals with ES.

6. Summary and concluding remarks

Awareness needs to be raised about the vital contribution of biodiversity and ES for crop production and food security. Our proposed model integrates ES in a structural production function alongside agrochemical inputs such as pesticides and fertilisers. Building on standard microeconomic theory, we extend the model based on ecological evidence to narrow the gaps in the current production economic paradigm. The framework captures the substitutability of management practices to provision biophysical conditions for crop growth, i.e., weed control, pest control, and soil fertility.

Empirical estimations of the productivity of biodiversity and its resulting ES as well as the efficiency of management practices requires appropriate data. Intensive practices are typically well documented at the farm level because farmers keep track of labour hours, capital use, and inputs in farm management software and are in some countries legally obliged to record their pesticide use. However, these data are not public but have to be gathered in farm surveys by researchers. Characterising ecological aspects are also time consuming and costly and directly measuring the function of interest might prove impossible. We provide an overview of economic and ecological proxies ranging from the ideal measurement to the most readily available measure to measure production factors that are either latent or too complex to measure directly.

In conclusion, our model explicitly captures the critical link between biodiversity, agricultural production, and sustainability. Understanding economically rational resource allocation decisions and their ecological implications, particularly when considering legacy effects from decades of intensive management, is essential to inform policies that support farmers to transition to ES-based more sustainable farming.

CRediT authorship contribution statement

Anne Sophie Dietrich: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Valeria Carini:** Writing – review & editing, Writing – original draft, Visualization. **Giulia Vico:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Riccardo Bommarco:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Helena Hansson:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no competing interests to declare.

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Appendix A. Appendix

To operationalise the model, research is needed to identify functional dependencies, i.e., the shape of curves, of the variables described in Table 1. Production economic research is typically based on flexible functional forms, such as translog or quadratic production functions, since the effect of each input in those models is relatively easily measurable using econometric techniques in form of linear regression models (Zhengfei et al., 2006). However, the choice of functional form of the production model has extensive implications on the shape of isoquants, and the extent of elasticities of factor demands and factor substitution (Fried et al., 2008; Lichtenberg and Zilberman, 1986). Ultimately, statements on how well ES substitute of anthropogenic inputs depend greatly on functional forms and hence misspecifications should be avoided. Semiparametric and parametric models, which are less restrictive and place almost no assumptions on the distribution of the data, can be used to fit flexible curves. Since no functional specifications are needed, our proposed model can be estimated even though the true relationship between variables are unknown or difficult to specify. Another advantage of non-parametric methods is their efficiency even for smaller sample sizes, which is a likely case even when collecting second-best indicators compared to estimations based on register data

Ecological theory suggests that output depends on relatively fixed proportions of inputs (Jonsson et al., 2014). Due to the productivity growth enabled by continuous development of machinery, agrochemicals, and advisory services, it is likely that the majority of farmers have reach a plateau in productivity (Lobell et al., 2009; van Ittersum et al., 2013), in which the input with the lowest supply determines output levels. Substitution between factors is unlikely, e.g., soil fertility cannot replace weed control and vice versa. In other words, if one or more factors are restricted, production will be limited despite all other factors being optimal (see Fig. 3) (Bommarco et al., 2013; Jonsson et al., 2014). In terms of a Constant Elasticity of Substitution (CES) production function, this implies that the substitution parameter ρ tends to negative infinity. Consequently, the isoquants, which depict feasible combinations of inputs yielding a specific level of output, might be (close to) L-shaped, suggesting a Leontief production technology. In microeconomic settings, these functions are rather uncommon due to their restrictive assumptions. However, in ecology and agronomy, these models are also known as Plateau or von Liebig Models and frequently used when depicting crop responses to irrigation water or nitrogen (Dhakal and Lange, 2021; Moeltner et al., 2021; Xu et al., 2019). Future research should explore whether the possibility to capture nonlinear relationships between variables of parametric models outweigh the risk of overfitting as well the simplicity and efficiency of linear regression models.

The functions of net services for weed control, pest control, and soil fertility should allow for a larger degree of substitution between production factors, i.e., ES and anthropogenic management. This is based on evidence that agrochemical inputs can (imperfectly) replace ES and vice versa (Brady et al., 2015; Fiedler et al., 2008). However, future research should identify methods to avoid simultaneity bias since the effectiveness of ES and anthropogenic inputs influence each other. An extension of the model can also take the interaction of different ES and into account, however, this adds substantial complexity.

Appendix B. Appendix

In the long-run, effectiveness becomes a function of past management. Over time, the effectiveness of corrective weed, pest, and soil fertility management α^c_{WC}, α^c_{PC} and α^c_F are decreasing in the historical predominance of corrective management. This is due to emerging resistances against plant protective products, loss of biological control, increase in competitive weeds and pests, and the depletion of soil in simple rotations with mineral fertiliser (Harker and O'Donovan, 2013; MacLaren et al., 2020; R. G. Smith, 2015). When used excessively, pesticides may even have opposing effects leading to even worse pest and weed outbreaks (Oerke and Dehne, 2004). This implies that in order to maintain the steady state, more inputs are needed to compensate low levels of effectiveness. At the same time, the effectiveness of corrective weed, pest, and soil fertility management α^c_{WC}, α^c_{PC} and α^c_F are increasing in the historical predominance of preventative management, as it implies that agrochemicals are only applied selectively, preventing overuse and resistances

Similarly, high values for the effectiveness of corrective weed, pest, and soil fertility management α^c_{WC}, α^c_{PC}, α^c_F, and the effectiveness of preventative weed, pest, and soil fertility management α^p_{WC}, α^p_{PC}, α^p_F imply that ES-based management is highly effective due to relatively high levels of local relevant biodiversity, the absence of competitive weeds, and dominant pests (Albrecht et al., 2020; Bommarco et al., 2013; Fiedler et al., 2008). Intuitively, in the long-run, the effectiveness of corrective and preventative weed, pest, and soil fertility management are decreasing in the historical predominance of corrective management due to the negative impact on local biodiversity, and increasing in the historical predominance of preventative management. Frequent and intense disturbances caused by agricultural management practices such as tillage, pesticide applications, and harvests result in a recovery and growth of plant (and animal) communities in an area that has undergone disturbance, with organisms gradually colonising and re-establishing the ecosystem (Odum, 1969; R. G. Smith, 2015). The regular reconfiguration of ecosystems after disturbance decreases soil health and local biodiversity required for pest regulation, and instead encourages the increase of highly competitive weeds and pests. Hence, progressively more management energy is needed to uphold a beneficial state for the target crop (Crews et al., 2016; R. G. Smith, 2015).

Data availability

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

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