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REVIEW ARTICLE

Model-based design of crop diversification through new field arrangements in spatially heterogeneous landscapes. A review

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Abstract

Intensive agriculture in Germany is not only highly productive but has also led to detrimental effects in the environment. Crop diversification together with new field arrangements considering soil heterogeneities can be an alternative to improve resource use efficiency (RUE), ecosystem services (ESS), and biodiversity. Agroecosystem models are tools that help us to understand and design diversified new field arrangements. The main goal of this study was to review the extent to which agroecosystem models have been used for crop diversification design at field and landscape scale by considering soil heterogeneities and to understand the model requirements for this purpose. We found several agroecosystem models available for simulating spatiotemporal crop diversification at the field scale. For spatial crop diversification, simplified modelling approaches consider crop interactions for light, water, and nutrients, but they offer restricted crop combinations. For temporal crop diversification, agroecosystem models include the major crops (e.g., cereals, legumes, and tuber crops). However, crop parameterization is limited for marginal crops and soil carbon and nitrogen (N). At the landscape scale, decision-making frameworks are commonly used to design diversified cropping systems. Within-field soil heterogeneities are rarely considered in field or landscape design studies. Combining static frameworks with dynamic agroecosystems models can be useful for the design and evaluation of trade-offs for ESS delivery and biodiversity. To enhance modeling capabilities to simulate diversified cropping systems in new field arrangements, it will be necessary to improve the representation of crop interactions, the inclusion of more crop species options, soil legacy effects, and biodiversity estimations. Newly diversified field arrangement design also requires higher data resolution, which can be generated via remote sensing and field sensors. We propose the implementation of a framework that combines static approaches and process-based models for new optimized field arrangement design and propose respective experiments for testing the combined framework.

Keywords Crop diversification · Agroecosystem models · Crop models · Patch cropping · Ecosystem services · Biodiversity

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Contents

1 Introduction

Agriculture in Germany is highly productive and characterized by increasingly mechanized large farms (average farm size in 2020 was 64 ha), producing 50 billion Euros in goods per year (Destatis 2021). Crop rotations have been simplified in the last decades (Barbieri et al. 2017) due to the introduction of mineral fertilizers, plant protection products (PPPs), and progress in plant breeding, which allows farmers to rely less on crop rotations for pest and weed control (Andert et al. 2016; Melander et al. 2013). Crop production patterns have been additionally influenced by farm specialization, market demands, priority for short-term profitability, availability of labor (Gutzler et al. 2015), and agricultural policies (Bauböck et al. 2014; Steinmann and Dobers 2013). The resulting systems are heavily dependent on external inputs and have led to a series of environmental problems jeopardizing the ecosystem service (ESS) delivery, related to provisioning of food, fiber, fuel, soil fertility, and water quality (Barbieri et al. 2017; Stoate et al. 2001). Excessive PPP application has caused detrimental effects to biodiversity and pollution of water bodies (Concepcion et al. 2020; Dudley et al. 2017; Tang et al. 2021). Moreover, the yield losses and yield variability associated with climatic extremes increased in recent years (Luttger and Feike 2018; Olesen et al. 2011; Webber et al. 2020).

Spatial and temporal crop diversification of cropping systems offer multiple benefits to the delivery of ESS, with mostly positive impacts on soil fertility and structure (Tamburini et al. 2020), crop yield (Anderson 2005), yield stability (Gaudin et al. 2015; Weih et al. 2021; Zampieri et al. 2020), nitrogen (N) cycling (Luce et al. 2020), carbon sequestration (Hazra et al. 2019; Tamburini et al. 2020), pest control (Letourneau et al. 2011; Lin 2011), biodiversity (Beillouin et al. 2021), and reduced yield risk (Feliciano 2019; Gaudin et al. 2015). Realizing greater benefit from crop diversification in these regards can be supported with the development of field robotics in the coming years allowing smaller field sizes and diversified agricultural landscapes. The resulting multifunctional landscapes would balance benefits and tradeoffs in ESS through consideration of natural variabilities in soils and other site characteristics (Basso and Antle 2020). Smaller field sizes (i.e., patches) are associated with multiple benefits to ecosystems, especially for biodiversity and species richness (Concepcion et al. 2020; Fahrig et al. 2015; Torres et al. 2020). Diversified landscapes via smaller patches (field units with a particular structure and function within the landscape), and additional landscape elements (i.e., hedgerows, flower strips) promote farmland biodiversity and pest regulation (Albrecht et al. 2020; Fahrig et al. 2015; Salek et al. 2018; Scheiner and Martin 2020; Sirami et al. 2019; Tscharntke et al. 2021). Spatial and temporal diversification in new field arrangements considering soil heterogeneity across landscapes can be an option to improve resource use efficiency as resources can be allocated according to the specific field characteristics in turn improving the delivery of ESS (Basso et al. 2013; Kersebaum et al. 2005; Tripathi et al. 2015).

Agroecosystem models are mathematical tools that simulate crop growth and development and soil processes in response to environmental conditions (radiation, temperature, water availability and retention, atmospheric CO_2, and nutrient availability from soils) and management practices (crop-cultivar selection, sowing dates, fertilizer applications, irrigation, etc.), typically using daily time step routines (Muller and Martre 2019; Rotter et al. 2015). They started to be developed in the 1960s and have evolved to include more complex approaches with improved representation of soil-plant-atmosphere dynamics. Agroecosystem modelling can be a powerful complementary method to field experiments, as virtual experiments can inform subsequent field experimentation (Boote et al. 2010; Kersebaum et al. 2015; Lobell et al. 2009). Such models are also helpful to scale up impacts from local (field experimentation) to landscape and regional levels (Duru et al. 2015). In this context, the main goal of this study is to review the extent to which agroecosystem models have been applied to (1) understand and design new arrangements of crops to increase crop diversity at the field and landscape scale by considering natural field heterogeneities in various soils; (2) quantify the effects of new arrangements of crops on resource use efficiency, ESS, and biodiversity; and (3) to specify requirements of models needed to be useful for these applications.

2 Methodology

In a first step, the definitions of the scales of crop diversification were defined from available publications (Andrews and Kassam 1976; Gliessman 1985; Hufnagel et al. 2020; Lin 2011). Most definitions within the sources were similar, though discrepancies were sometimes found. For example, for the intercropping definition, references agree that it is a measure of simultaneously growing two or more crops in the same field, but Hufnagel et al. (2020) consider proximate rows arrangement while Gliessman (1985) also considers intercropping when growing two crops with no distinctive row arrangement. Thus, intercropping in this review was defined as crops simultaneously growing in the same field with or without distinctive row arrangement. Despite that a wide range of agroecosystem models exist with varying structure and complexity, we selected some widely used agroecosystem models based on their ability to simulate a degree of spatial and/or temporal crop diversification. We note that many other models with varying complexity and structure could have also been considered. The models were selected by first identifying agroecosystem models used in model intercomparison publications, projects, and expert knowledge reported in the Web of Knowledge and Google Scholar. Most of the agroecosystem models considered in this review are process-based and comprise the soil-plant-atmosphere compendium for arable crops (examples for agroforestry were also included as they are an example of spatial crop diversification). They explicitly include daily dynamics for crop phenology, crop growth, soil water, N balance dynamics, and soil carbon and with multiple parameterized crop species. They have been developed with the objective to describe (in an explanatory or "mechanistic" manner) either the impact of climate variables, soil and crop management or a combination of all on the growth and productivity of crops and cropping systems at the field scale, assuming homogeneous soil conditions. In a next step, we considered if the models had publications in their application relevant to crop diversification either in system design or evaluation. As for the quantification of ESS considered in the models, we described them according to the processes and variables simulated by the models. It should be noted that many models considered as agroecosystem models in this study are widely known as crop and cropping system models. Differences among these models and agroecosystem are not further addressed here as they are not crucial for the aim of this review. As these model categories are also often used interchangeably, all models are referred to as agroecosystem models. Very specialized models simulating only, for example, pesticide leaching (Bergstrom and Jarvis 1994; Gassmann 2021), soil erosion by water (Jarrah et al. 2020; Raza et al. 2021), or soil carbon sequestration (Falloon and Smith 2002; Foereid and Hogh-Jensen 2004; Jenkinson and Coleman 2008) were not considered in this review as they are too limited in the range of ESS that can be simulated. Other simulation approaches such as functional-structural plant models (Vos et al. 2010) were not included in this review as they typically exclude nutrient or water dynamics. At the landscape scale, a similar approach was used, but it yielded limited results. Therefore, the search was extended to the use of decision support tools, decision-making frameworks, and landscape generators that also focused on the design of spatio-temporal crop diversification. The selection of frameworks includes some of the most popular frameworks for the design of crop diversification at the farm and regional scale.

3 Spatial and temporal crop diversification at the field and landscape level

3.1 Concepts of crop diversification

Definitions around the spatial and temporal diversification of cropping systems at field scale as considered for the current review are described in Figure 1. Spatial crop diversification can be achieved by growing different crop cultivars and species in different configurations at the same time in a given field. Temporal crop diversification involves the implementation of crop rotations or crop sequences (growing a sequential set of crops in the same land). A definition of landscape can be ambiguous and depends on the context of the study. Forman (1995) defined landscapes as a mix of local ecosystems or land use types that is repeated over a certain area of land. Marshall (2008) defined them as mosaics of farm fields, semi-natural habitats, human infrastructures, and occasional natural habitats. Meeus (1995) defined landscapes as recognizable parts of the Earth surface, which have a characteristic composition, structure, and scenery. Depending on the region, in Germany, landscapes in the west of the country are characterized by small farms (average size of about 60 ha) whereas in the east they are characterized by bigger farms (about 230-ha size on average) due to historical management reasons. For our review, the landscape scale is considered for simulation approaches that attempt to design diversified cropping systems in an area encompassing at least several crop fields (a single field is delimited by barriers such as field hedges, hedgerows, or streets) and farms, though we recognize that in actual assessments of cropping system diversification at

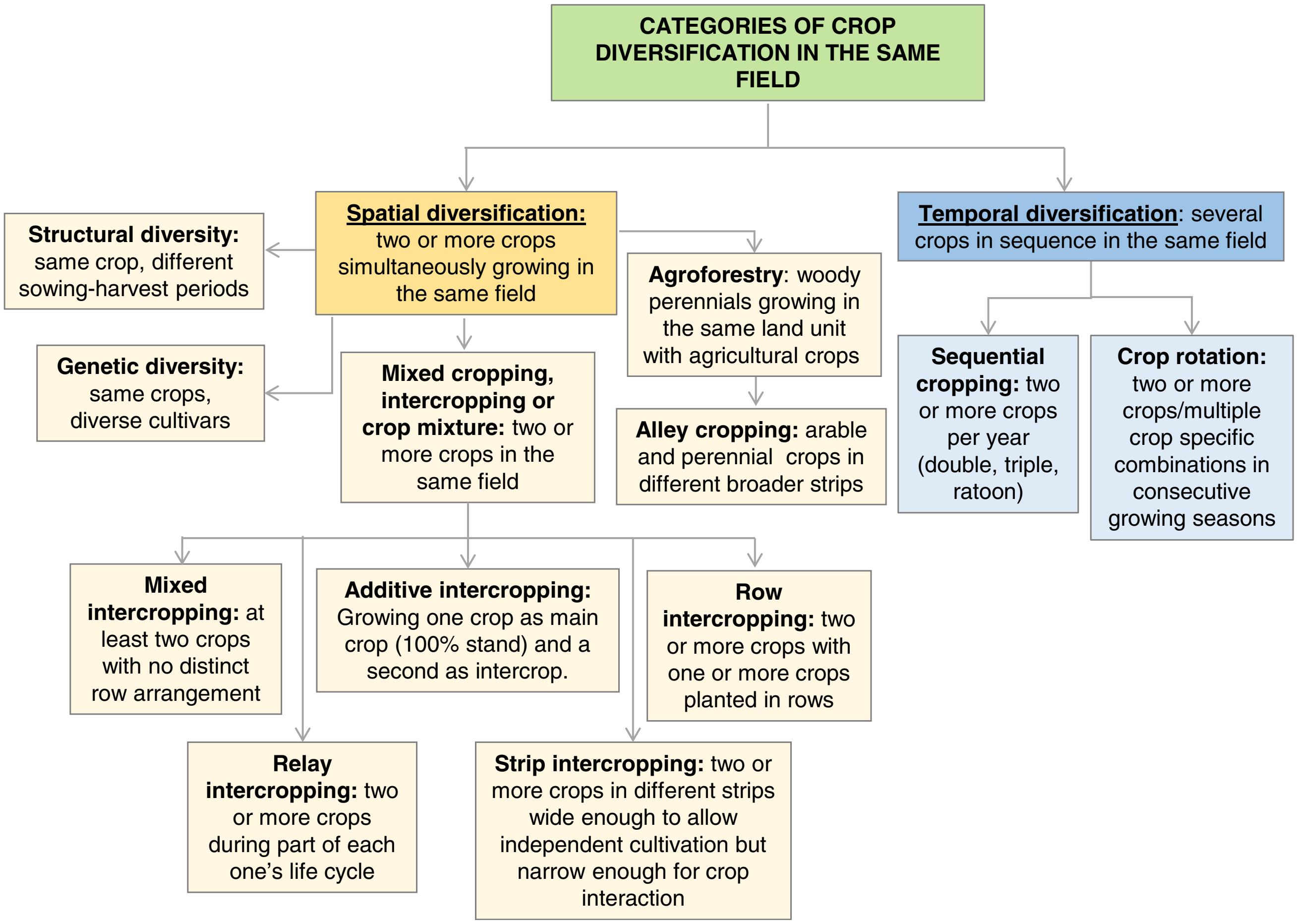

Fig. 1 Categories of spatial and temporal crop diversification (also defined as polyculture) at the field scale, alternative to sole cropping (growing a single crop in a field) and monocropping (growing a single crop in an entire field overtime).

landscape scale other social, ecological, and economic characteristics of landscapes require consideration. Spatial crop diversification at the landscape scale is typically described by landscape configuration and composition. Landscape configuration refers to the spatial pattern of the landscape in terms of size, shape, and spatial arrangement of structural elements (e.g., fields, semi-natural habitats, and hedgerows), while landscape composition refers to the type and abundance of the spatial elements within the landscape. Similar to the field scale, temporal crop diversification at the landscape scale is also achieved by the diversity of crop rotations and sequences at the field scale.

3.2 Approaches to simulate spatial diversification of crop species

The benefits of spatial crop diversification at the field and landscape scale have been widely studied. Crop mixtures generally show improved nutrient use efficiency due to their competitive and facilitative species interactions that result in higher crop yields per unit area than sole cropping (Zhang and Li 2003). Legume presence in intercropping is known to be beneficial due to the biological N fixating characteristics and their contribution to P mobilization. The later arises with the acidification of the rhizosphere caused by the legume (faba bean in particular) root release of organic acids and protons (Li et al. 2007). Diversified systems increase stability in terms of grain yield and gross margin income even in low input systems (Bedoussac et al. 2015; Brooker et al. 2015). They contribute to weed suppression due to resource competition, allelopathic interference, soil disturbance, and mechanical damage (Liebman and Dyck 1993). Intercropping reduced disease incidence by more than 70% when comparing monocrops vs intercropped systems (Boudreau 2013).

A wide repertoire of agroecosystem models have been developed over the last decades, but few of them are capable of simulating spatial crop diversification that includes the interaction of different crop species (Gaudio et al. 2019). While there is no single smallest spatial scale for agroecosystem models, as they generally simulate canopy characteristics expressed on a per 1m^2 basis, plant level characteristics at finer scale can be achieved when using 3D functional-structural plant models (Evers et al. 2019; Vos et al. 2010). These later models simulate plant structures and their physiological interactions at the individual plant level and also offer the possibility to theoretically explore specific genetic traits related to plasticity, competition, and niche complementarity (Gaudio et al. 2019). However, they generally do not account for crop management practices, which is a strength in agroecosystem models.

Genetic diversity in a field (Figure 1) can be simulated by all agroecosystem models considered for this study, typically by using a set of parameters to define the crop phenology (as affected by temperature, photoperiod, and vernalization) and yield potential for specific cultivars. The approach has been used for major crops such as wheat, barley, and rice to identify cultivars better adapted to specific environmental conditions (Casadebaig et al. 2016; Semenov and Stratonovitch 2015; Tao et al. 2017). For mixed cropping or crop mixtures (i.e., simultaneous growth of at least two crops sharing partially the same space at the same time, Figure 1), some models can simulate diverse spatial configurations depending on the degree of crop interaction; species consideration depends on the specifics of each model. For crop mixtures with sufficient space between adjacent crops such that competition of resources is limited (e.g., alley cropping, row, or strip intercropping), it is possible to simulate them with agroecosystem models intended for sole crops. However, for crop mixtures where crops are close enough to interact (e.g., intercropping, relay intercropping, or additive intercropping), only seven models of the selection considered here (APSIM, CropSyst, Daisy, DNDC, EPIC, FASSET, and STICS) are capable of simulating such systems, albeit with relatively simplified assumptions about above and below ground crop interactions of light, water, and nitrogen recourses (Table 1). Light competition is often implemented by dividing the crop canopy in compartmental layers (minimum two layers) and assigning dominant and shaded canopy structures; the total simulated canopy is proportional to the canopy contribution of each species; the dominant specie is determined typically by plant height and it is constant during the cropping cycle, though in reality crop dominance may switch during the season (Spitters and Aertes 1983). Belowground competition for water and nutrient uptake are mostly based on relative root length of the interacting crops, soil water, N availability, and crop demand. The parameters required for the simulation of intercropping systems in the models considered are generally crop species specific, and limited to combinations of two crops, restricting the number of crops available for possible intercropping arrangements. Generally, no further interactions beyond resource competition (e.g., root exudates influencing microbial activity) are considered. Another form of intercropping is agroforestry, where trees and crops are grown together to benefit from the neighboring above- and below-ground interactions for resources (Ong et al. 1991). Available agroforestry models include WaNulCAS and Hi-sAFe (Table 1), which are reviewed in detail together with other available agroforestry models by Luedeling et al. (2016). Part of their limitation relies on the lack of model flexibility to be adapted to different environments, the extensive parameterization and sometimes the lack of model maintenance, which are issues that need to be addressed for future model applications.

Depending on the agroecosystem model, it is possible to dynamically simulate a set of provisioning and regulating ESS (Table 1) for spatially diversified cropping systems. For instance, all considered models can simulate the provisioning of food, feed, fiber, or fuel (via biomass simulation). The GHG regulation through the simulation of soil carbon sequestration is widely considered in the selected models, but N_2O emissions are considered in just thirteen of the selected agroecosystem models (Table 1), examples are CropSyst, DNDC, STICS, EPIC, and APSIM. Furthermore, no models consider measurable particulate and mineral-associated organic matter pools that are widely considered in the soil organic matter modelling community, and rather simulate conceptual carbon pools that follow first order decay functions. Simulation of water quality by simulating soil N retention (via N leaching dynamics) is possible for most models considered here, except for AquaCrop which lacks an explicit component to simulate N balance. Pesticide fate is considered in few of the selected models (CropSyst, Daisy, EPIC, FASSET, and APSIM), as well as soil conservation by quantifying soil erosion (SWIM, CropSyst, EPIC and Hi-sAFe). One of the drawbacks when using agroecosystem models for crop mixture design is the limited understanding and model representation of species-specific ecological and physiological processes, such as niche complementarity, phenotypic plasticity, facilitation, and competition (Gaudio et al. 2019; Malezieux et al. 2009). No ESS related to pest control, pollination, and biodiversity are considered for the set of studied models.

For spatial crop diversification at the landscape scale, the minimum scale of diversification is typically a whole field or "patch" (Langhammer et al. 2019). Landscape generators are tools used in Ecology to generate virtual agricultural landscape maps for exploring spatio-temporal dynamics of land use change. A landscape generator typically considers different agricultural land use systems including natural, semi-natural habitats, crop land, and landscape elements. The most common approaches to create such landscape maps are either pattern based (using generic algorithms that generate realistic virtual maps with no consideration of ecological processes) or process based (generate maps given a specific ecological process to be addressed) (Langhammer et al. 2019). For both approaches, the crop types and their spatial allocation are conducted using stochastic or static approaches or assembling crop generators. Crop-related processes for either sole crops or intercropping are poorly or not represented. Other models are built and applied for specific ecological questions. For

Table 1 Agroecosystem simulation models for the evaluation of spatial and temporal crop diversification at the field scale: approach, available crops, and currently simulated ecosystems services (ESS). *GHG* greenhouse gasses. *Type of div.* type of diversification: *SPAT* spatial, *TEMP* temporal, and *AGROF* agroforestry.

Model/Reference	Type of div.	Type of diversification	Approach	Available crops	Provision of ESS	Regulation of ESS
APSIM (Holzworth et al. 2014; Keating et al. 2003)	SPAT	Mixed intercropping (Berghuijs et al. 2021; Nelson et al. 2021a; Nelson et al. 2021b)	"Arbitrator" module for species allocation of light and soil water and N. Various canopy layers defined, leaf area distribution increases with crop height, regulating light interception.	Only a combination of two crops in one simulation run. A maximum of 10 crops available for combination.	Food supply, feed, fiber, and/or fuel (top biomass, crop yield, weeds).	Water quality (N retention, pesticide fate) GHG (N_2O emissions and soil carbon sequestration); Soil conservation (groundcover)
	TEMP	Rotation (Hoffmann et al. 2018; Yang et al. 2018)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	>23 crops (5 cereals, 12 legumes, 2 oil crops, cotton, hemp, sugarcane, forest, and pasture).	Food supply, feed, fiber, and/or fuel (top biomass, crop yield, weeds)	Water quality (N retention, pesticide fate); GHG (N_2O emissions and soil carbon sequestration); soil conservation (groundcover); landscape (via crop rotation)
CropSyst (Stockle et al. 2003; Stockle et al. 2014)	SPAT	Mixed intercropping (Carlson et al. 2016)	Canopy divided in above, within/below, and shorter canopy. Water and N demand controlled by a "Competitiveness factor"	Only a combination of two crops in one simulation run. Examples for maize-bean intercropping.	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (N_2O emissions and soil carbon sequestration); soil conservation (erosion)
	TEMP	Rotation (Diaz-Ambrona et al. 2005; Garofalo et al. 2009)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	>10 crops (5 cereals, 5 legumes, sugar beets, sunflower, potatoes).	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (N_2O emissions and soil carbon sequestration); soil conservation (erosion)
Daisy (Abrahamsen and Hansen 2000)	SPAT	Mixed intercropping (Manevski et al. 2015)	Light distribution proportional to the crop's contribution to the total LAI. Water and N competition based on the root depth and distribution and limited by the available soil N.	Only a combination of two crops in one simulation run. Examples for cereal-legume combinations	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (soil carbon sequestration)
	TEMP	Rotation (Manevski et al. 2016),	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for pea and catch crops (rye, Italian rye grass, winter rape, oil radish)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (soil carbon sequestration); landscape (via crop rotation)
DNDC; China DNDC; DNDC95; LandscapeDND-C (Hu et al. 2017, Haas et al. 2013)	SPAT	intercropping (Zhang et al. 2018)	Crop parameters adjustment for maximum biomass production, biomass fractions, Biomass C/N ration, water demand and fixation index in the case of legumes	Example for maize and soybean	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions, soil carbon and carbon sequestration).

Table 1 (continued)

Model/Reference	Type of div.	Type of diversification	Approach	Available crops	Provision of ESS	Regulation of ESS
	TEMP	Rotation (Abdalla et al. 2022; Jiang et al. 2021)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for twenty-three major crops including, cereals (maize, wheat, hay, sugarcane, barley, sorghum), legumes (soybean, alfalfa, peanut, bean), tubers (potato, sugar beet)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration); landscape (via crop rotation)
EPIC and EPICSEAR (Williams 1995)	SPAT	Mixed intercropping (de Barros et al. 2004, 2005	Considers light interception, energy conversion to biomass, water, and nutrient uptake, no consideration of crop-to-crop interaction.	Only a combination of two crops in one simulation run. Examples for maize-cowpea intercropping	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (N2O emissions and soil carbon sequestration); soil conservation (erosion); landscape (via crop rotation)
	TEMP	Rotation (Gaiser et al. 2008)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period	Generic crop growth routine	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention, pesticide fate); GHG (N2O emissions and soil carbon sequestration); soil conservation (erosion); landscape (via crop rotation)
FASSET (Berntsen et al. 2003)	SPAT	intercropping (Berntsen et al. 2004)	Light interception of the mixture is based on a multilayer light competition model for leaf dispersion as function of downward LAI and extinction coefficient. Plant uptake for water and N is assumed to depend on plant demand, resource amount and potential uptake.	Example for pea and barley	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration);
	TEMP	Rotation (Doltra et al. 2019)	Farm model, modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for wheat, barley, grass, sugar beet	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration);
STICS (Brisson et al. 2003)	SPAT	Mixed intercropping (Brisson et al. 2004; Launay et al. 2009)	Plant canopy subdivided in dominant and the understory canopy (sunlight and shaded part). Same soil compartment for both crops, interactions based on each crop profile root penetrability and water content dynamics.	Only a combination of two crops in one simulation run. Examples for grass-cereal combinations, cereal-legume combination	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N_2O emissions and soil carbon sequestration)
	TEMP	Rotation (Plaza-Bonilla et al. 2017; Yin et al. 2020)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	>20 crop species (mayor cereals, legumes, and oil crops)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N_2O emissions and soil carbon sequestration); landscape (via crop rotation)
	TEMP					

Table 1 (continued)

Model/Reference	Type of div.	Type of diversification	Approach	Available crops	Provision of ESS	Regulation of ESS
Agro-C (Huang et al. 2009)		Rotation (Huang et al. 2009; Zhang et al. 2021)	Designed for regional scale, it consists of two sub models: Crop-C (simulates and Soil-C.	Crops include cereals, sugar beet, maize, potato, and grassland.	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); landscape (via crop rotation)
AGROTOOL (Poluetkov et al. 2002)	TEMP	Rotation (Badenko et al. 2017)	Biomass residue, nodule nitrogen (if predecessor is legume), total mineral N and humus are fixed at the end of the season and initialized at sowing of the following crop. limited on carrying out year to year dynamics.	Grassland, maize, wheat, barley, rye, sugar beet and catch crops (oil radish, yellow mustard, phacelia, winter rape)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration);
AquaCrop (Raes et al. 2009; Steduto et al. 2009)	TEMP	Rotations (Kostkova et al. 2021)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for major cereals (wheat, maize, rice), legumes (soybean) and tubers (sugar beet, potato)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Not applicable, nutrient-related dynamics not explicitly considered.
DAYCENT (Del Grosso et al. 2002)	TEMP	Rotation (Smith et al. 2008)	Daily time-step version of the CENTURY model; Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for major crops of cereals (maize, wheat, barley), legumes (soybean) and tubers (potato) and grasses	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration); landscape (via crop rotation)
DSSAT (Hoogenboom et al. 2004)	TEMP	Rotation (Gao et al. 2022; Li et al. 2015b)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	>40 crops (cereals, legumes, root crops, oil crops)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N_2O emissions and soil carbon sequestration); landscape (via crop rotation)
HERMES (Kersebaum 2011)	TEMP	Rotation (Kersebaum 2007)	Modular: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for mayor cereals, legumes, root crops, oil crops and grass, etc.	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); landscape (via crop rotation)
Hi-sAFe (Dupraz et al. 2019)	SPAT	Agroforestry (Artru et al. 2017)	3D model combined with STICS; three-dimensional with above and below ground interaction with interaction submodules of light, water, N, and microclimate	Tree-crop interactions, walnut, wild cherry, poplar, Mediterranean oaks with winter and summer annual crops, grass, and alfalfa.	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); soil conservation (erosion)
LPJmL (Bondeau et al. 2007)	TEMP	Rotation (Kollas et al. 2015)	Modular carbon vegetation model: For crop rotations, soil and litter carbon pools of new	11 arable crops and two managed grass types	Food supply, feed, fiber,	

Table 1 (continued)

Model/Reference	Type of div.	Type of diversification	Approach	Available crops	Provision of ESS	Regulation of ESS
			and existing agricultural land are mixed after harvest.		and/or fuel (top biomass and crop yield)	GHG (N2O emissions and soil carbon sequestration); landscape (via crop rotation)
MONICA (Nendel et al. 2011)	TEMP	Rotation (Nendel et al. 2014)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for mayor cereals, legumes, root crops, oil crops and grass, etc.	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); landscape (via crop rotation)
SALUS (Basso et al. 2006)	TEMP	Rotation (Basso and Ritchie 2015)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for major cereals (wheat, barley, maize), legumes (soybean) and tubers (potato)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); landscape (via crop rotation)
SIMPLACE framework (Addiscott and Whitmore 1991; Angulo et al. 2013)	TEMP	Rotation (Seidel et al. 2021)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Lintul5- adapted to >15 crops (6 cereals, 6 legumes, 2 root, 2 oil crops)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration); landscape (via crop rotation)
SPACSYS (Liang et al. 2019; Wu et al. 2007)	TEMP	Rotation (Perego et al. 2016)	Multidimensional model with a 3D root model, no carry out of soil processes.	Examples for major cereals	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (N2O emissions and soil carbon sequestration); Soil conservation (surface runoff); landscape (via crop rotation)
SWAT+EPIC; SWAT-C (Arnold et al. 2012; Krysanova and Arnold 2008)	TEMP	Rotation (Gao et al. 2017)	For local and Basin scale; Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	More than 45 annual and perennial crops (7 cereals, eighteen grasses, 12 legumes, 4 root crops, 4 oil crops)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); GHG (soil carbon sequestration); landscape (via crop rotation); soil conservation (erosion by water)
SWIM (Krysanova et al. 2015)	TEMP	Rotation (Krysanova and Haberlandt 2002)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period. With a crop rotation generator	74 crop/vegetation types (agricultural crops and natural vegetation)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); Soil conservation (erosion); landscape (via crop rotation)
THESEUS (Wegehenkel et al. 2004)	TEMP	Rotation (Wegehenkel et al. 2004)	Modular approach: Soil nutrient and water dynamics are carried out during the simulation period.	Examples for major cereals and root crops	Food supply, feed, fiber, and/or fuel (top biomass	Water quality (N retention); landscape (via crop rotation)

Table 1 (continued)

Model/Reference	Type of div.	Type of diversification	Approach	Available crops	Provision of ESS	Regulation of ESS
					and crop yield)	
WaNuLCAS (Van Noordwijk and Lusiana 1998)	AGROF	Agroforestry (Wise and Cacho 2005)	Modular approach; Different geometries and temporal patterns. Above and below ground crop interactions. Zerosink model to simulate competition for combined root uptake, plant uptake based on individual supply and demand.	>10 crops (examples for cereals, root crops and leguminous plants)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); (soil carbon sequestration)
WOFOST (Vandiepen et al. 1989)	TEMP	Rotation (Marletto et al. 2007)	Different routines/not fully modular. No carry over effects of soil nutrients and water.	>22 crops (mayor cereals, legumes, root crops, oil crops)	Food supply, feed, fiber, and/or fuel (top biomass and crop yield)	Water quality (N retention); landscape (via crop rotation)

example, BEEHAVE considers field arrangement design for landscape configuration and composition for foraging crops, used as pollen sources for bees (Becher et al. 2014, 2018). Holzkamper et al. (2006) implemented a spatial optimization model for land use change tradeoffs between species habitat suitability and management, with the implementation of a genetic algorithm approach to identify the optimum land use configuration of grassland, cropland (with no crop specification), and forests for specific bird species in Northwest Saxony, Germany. The optimum set-up for species habitats and management was provided by smaller patches and greater diversity of land use including more forest lands and decreased grassland and cropland.

3.3 Approaches to simulate temporal crop diversification

Temporal crop diversification through crop rotations or sequences offers multiple benefits for agricultural systems such as improved resource use efficiency (Anderson 2005; Pierce and Rice 1988), improved soil structure from incorporated crop residues, soil bio-pores and soil microbial dynamics (Ball et al. 2005), reduced weed and pest incidence (Brust et al. 2014), and reduced risk of crop failure (Helmers et al. 2001). Crop rotations have an impact on short- and long-term legacy effects of water and nutrient balances, soil carbon storage, and crop productivity (Basso et al. 2020). Crop sequence effects on yield can persist for 3–4 years in dry years or semi-arid environments as a result of water and nutrient legacies (Kirkegaard and Ryan 2014). Grass et al. (2015) investigated the opportunities of using double cropping systems for biomass production and found increasing water limitations for the second main crop under projected climate change. Carry-over effects for water may play an increasing role in crop rotation design even in presently humid climates, e.g., limiting establishment of catch crops in dry summers. Crop rotation legacy also includes effects of inoculum survival and subsequent infestations of crops with fungal diseases. There is evidence that herbicide and fungicide use is lower in more diverse crop sequences (Andert et al. 2016).

Agroecosystem models can be used to simulate some of these crop rotation effects on crop yields, resource use dynamics, and their efficiency. To date, their primary contribution to system design is on the evaluation perspective for particular crop rotations selected by the model user; one rare example is the SWIM model, which includes a crop rotation generator (Krysanova et al. 2015). More than twenty of the selected models can dynamically simulate crop rotations. Many allow simulation of multiple crops including major cereals (wheat, maize, barley, rice, sorghum, millet), legumes (soybean and cover crops), oil (sunflower, rapeseed), and sugar producing crops (sugarcane and sugar beet) (Table 1). The models can simulate reasonably well the soil N and water dynamics over a full rotation period. The selected models vary with respect to the set of ESS they can simulate. All include simulation of provisioning of food supply, feed, fiber, or fuel (Table 1). The majority can account to some degree from climate change mitigation through simulation of soil carbon sequestration (except for WOFOST), while about half of the model*s* include the regulation of GHGs by simulating N_2O emissions (e.g., APSIM, DSSAT, EPIC, STICS, and WOFOST). Water quality through pesticide fate (APSIM, CropSyst, DAISY, EPIC) and soil conservation by quantification of soil erosion (Hi-sAFe, SWAT, SWIM, EPIC, and CropSyst) are not often considered in the models (Table 1). None of the models included in this review accounts for phytosanitary aspects, e.g., rotation design and management effects on the survival of pests and diseases.

Model capacity can be limited when simulating crop rotation dynamics for the long term, particularly for soil N, C, and water. Kollas et al. (2015) performed a fifteen-model intercomparison exercise to simulate crop rotations (including ten crop types) for five locations in Europe. Agroecosystem models performed slightly better when considering carry-over effects (initializing the model just at the beginning of the rotation period) of the rotations. However, model limitations with regard to N release from residue mineralization, dynamics of soil organic matter, tillage effects, and number of crops often limited model performance. Model skill may be also limited by the lack of catch or cover crops parameterization (Kollas et al. 2015; Yin et al. 2017) and the representation of fallow processes, where experimental data has typically not been available for model calibration. This highlights both the need of high-quality data as well as model improvement for further applications around designing temporal crop diversification.

At the landscape scale, examples of the applications of agroecosystem models in combination with land use models or water basin models for the optimization of crop rotations are available. For example, Lawes and Renton (2015) combined the Land Use Sequence Optimizer (LUSO) model, which is a bioeconomic framework, with the APSIM agroecosystem model in the optimization of crop rotations. Johnson et al. (2009) combined the SWAT model with the ALMANAC agroforestry model to improve the simulation of agroforestry system within a water basin. The DSSAT model has been implemented at regional scales for the evaluation of crop rotations (Gao et al. 2022; Hu et al. 2014). The ACLIReM (a statistical tool), CropRota (a rotation generator), and the EPIC model were combined for the optimization for cropping systems including crop rotations at the spatial scale (Mitter et al. 2015). The approach just involves crop rotation optimization; smaller degree of crop diversification within a field is not considered.

Other non-dynamic approaches at the landscape involve static-rule frameworks that can support the design of temporal crop diversification at larger spatial scale (Table 2). Most follow an optimization criterion based on agronomic or economic factors, others additionally include environmental and social components. A predetermined list of crops, with their respective site-specific management information, is typically included in the framework. Crop selection and allocation are either based on common crop rotations for the specific study area or inclusion of a new crop to the rotations (e.g., CropRota). The rotation length can be restricted by the user. Within-field heterogeneities are not directly considered as typically the crop category would be assigned to a full plot with no finer subdivisions. Rotation length is based either on the site-specific data or restricted by the user. CropRota (Schonhart et al. 2011) and ROTAT (Dogliotti et al. 2003) are similar tools that optimize crop rotations based on agronomic criteria, but they differ as the CropRota tool limits the number of crop rotation options based on the common rotation set-up for a determined location, and it offers more flexibility to adapt the tool to different management options and environments. The ROTOR tool (Bachinger and Zander 2007) was created to design crop rotations for organic farms focusing on N and phytosanitary criteria for system optimization. The LUSO framework (Lawes and Renton 2010) additionally accounts for the optimization of crops rotations based on management or profitability as affected by weeds, diseases, and N supply. The assessment framework by Reckling et al. (2016) was designed with the main objective of introducing legumes to crop rotations and evaluating their performance with a set of environmental, economic, and phytosanitary indicators. Nemecek et al. (2015) developed a method for crop rotation design based on the life cycle assessment method, where crop combinations can be either common or new to the area of interest; they are evaluated based on agronomic criteria, pest incidence, and soil nutrient use. Other economic models such as the frameworks developed by Liu et al. (2016) and Li et al. (2015a) are frameworks to optimize crop rotations based on economic return but they also require information with regards to crops, management practices, and plant protection. Another recent framework based on economic optimization is the tool “Fruchtfolge” a web-based decision support system for Germany based on big data and spatially explicit modelling (Pahmeyer et al. 2020). Its aim is to suggest crop rotations and crop allocation based on field specific location factors, labor endowments, field-to-farm distances, and policy restrictions from the EU Common Agricultural Policy. The SYSTERRE® online tool (Berrodier and Jouy 2013) and MAELIA (high-resolution multiagent platform) also can be applied to study diversified cropping systems at the landscape scale, but their objective is the evaluation of spatial and temporally diversified cropping systems based on a set of technical, economic, and environmental factors. Even simpler approaches for landscape design such as sketch design exist. For example, Lovell et al. (2010) used this

Table 2 Examples of modeling frameworks for the design of temporal crop diversification through crop rotations at the farm and landscape scale.

Model	Reference	Model description	Optimization criteria
Assessment framework	Reckling et al. (2016)	System assessment framework using a static, rule-based rotation generator and algorithms to calculate impact indicators (environmental, economic, and phytosanitary). Designed for introduction of legumes into rotations.	Agronomic, environmental, economic, and phytosanitary
Crop Rota	Schonhart et al. (2011)	Linear optimization model for crop rotations (42 crops to select, 6 crops max. per rotation) and their distribution in the land. Rotations based on crop shares in a farm, region, or any other spatial unit for a specific time period (single or many years).	Agronomic
Dynamic optimization framework	Liu et al. (2016)	Economic dynamic optimization framework, includes agronomic, cultural practices, and plant protection for a specific farm with X number of equally sizes parcels.	Economic
Life cycle assessment (LCA)	Nemecek et al. (2015)	Life cycle assessment method. A set of crop combinations (typically or not typical to the region) are selected and evaluated based on agronomic criteria, incidence of diseases, and potential to use the nutrients left after harvest in the soil	Agronomic, economic, and ecological (N use)
LUSO	Lawes and Renton (2010, 2015)	Deterministic, bio-economic state and transition model for the optimization of crop rotations as affected by weed, diseases and N supply	Agronomic and economic
Operation model	Li et al. (2015a)	The model consists in an algorithm that selects the optimal crop rotations with a predetermine rotation period that would achieve maximizing prices and minimizing the profit differences for a set of farmers in a given region	Economic
MAELIA	Catarino et al. (2019, 2021)	MAELIA is a high-resolution multi-agent platform to simulate the dynamics and interactions of human activities, ecological processes, and governance systems either in a field or landscape scale. Designed to evaluate crop diversification based on a set of indicators.	Economic and environmental
MicroLEIS DSS	(De la Rosa et al. 2004)	Knowledge based framework with strong focus on soil biophysical characteristics comprising databases, statistic models, expert systems, neural networks, web, and GIS applications	Agronomic and environmental
ROTAT	Dogliotti et al. (2003)	Computer program to design crop rotations. The program combines crops from a predefined list (~30 crops) to generate all possible rotations based on filters and user restrictions.	Agronomic
ROTOR	Bachinger and Zander (2007)	Static rule-based model consists of a set of annual crop production activities from site and crop-specific field operations using a relational data base to model, all possible positions of a crop within a crop rotation is evaluated using rule-based modules.	Agronomic and economic performance
SYSTERRE	Jouffret et al. (2015) and Weber et al. (2019)	It describes innovative diversified cropping systems but also to assess their technical performances as well as their sustainability toward economic, social, and environmental pillars. Designed to evaluate crop diversification	Economic, environmental, and social

methodology to improve farm functionally through consideration of site mapping and surveys (biological, cultural heritage, and visual aspects) to determine the possibilities to integrate elements beneficial for the delivery of certain ESS by incorporating knowledge of landscape architects and ecologists. Few of these platforms include integration with agroecosystem models. However, the generated information can also serve for decision-making of cropping system design.

3.4 Crop species allocation considering within-field soil heterogeneities.

Spatial and temporal within-field soil heterogeneities lead to different patterns of crop growth response in agricultural fields (Hoffmann et al. 2017; Rossel and McBratney 1998). This remains underexplored in both experimental and modelling studies, particularly for understanding how to exploit this heterogeneity in allocating crops within a field or at landscape scale. Some areas may be more suitable for a given crop or crop rotation whereas other areas may be unsuitable for crop production due to a shallow ground water table, water logging, presence of deep sandy soils or rock fragments, and could be assigned for flower or non-vegetation crops to promote beneficial insects (Basso and Antle 2020; Koszinski et al. 1995; van der Kroef et al. 2020). One of the few examples at field scale for designing diversified cropping systems considering within-field heterogeneities is the approach used by Apeldoorn et al. (2019), who developed a model platform to evaluate and design strip cropping systems by using the soil organic matter content in combination with long-term crop yield data. Area configurations were evaluated using the bioeconomic FarmDESIGN-model (Groot et al. 2012) and the ROTAT (Dogliotti et al. 2003) crop rotation model was used to generate the crop rotations for the selected configuration. Finally, the StripRotation app considers the multifunctionality of crop rotations to evaluate and select optimal crop and field configuration. This type of decision support framework can be very useful as it combines decision-making tools, although it may be more limited when exploring interactions of the diversified system with crop management practices that may affect resource use efficiency and ESS delivery.

3.5 Spatial structural diversity of landscape elements of non-crop vegetation strips

Landscape elements, such as hedgerows and flower strips, are important contributors to biodiversity conservation as they increase plant diversity, facilitate species movement, and serve as a habitat for pollinators and beneficial insects for pest control (Hatt et al. 2017; Morandin et al. 2016; Tschumi et al. 2015; Vanneste et al. 2020). Landscape elements also play an important role in the regulation of wind and water erosion (Burel 1996). For landscape design, consideration offers an opportunity to use areas with poor or degraded soils to promote biodiversity (Basso and Antle 2020). Depending on their proximity to the crop, they facilitate infiltration of soil water to the crop, reducing erosion with loss of soil and nutrients. This effect can be simulated by agroforestry models, in which the dynamics of tree growth, crop growth, and above and below tree-crop interactions are considered. Efforts to couple agroecosystem models with agroforestry models have been carried out previously with the APSIM model (Huth et al. 2002, b; Keating et al. 2003; Luedeling et al. 2016). The challenges relate to the fact that trees typically have a larger vertical and horizontal influence than a typical crop (Luedeling et al. 2016). Additionally, there is a mismatch in the temporal resolution of simulations as the time-step of the simulation for trees can often be a year (Malezieux et al. 2009). In the case of flower strips, agroecosystem models are able to capture crop dynamics, but to date, few if any model evaluation studies have been reported. Particularly unclear is the modelling of gradient impacts from the strip borders into crop fields for crop yield as well as ESS and biodiversity. Schmidt et al. (2017) estimated that at the landscape scale, the effects of micro-climate and litter transfer to alter conditions in soils of transition zones to be 10–20 m and 25–50 m for above-ground space.

4 Required modelling capabilities for newly diversified field arrangements in heterogeneous fields and landscapes

4.1 Crop species/cultivars options in agroecosystem models

According to the FAO (1996), from 250,000 known plant species, about 120 plant species are cultivated for food with nine and three accounting for providing 75% and 50% of global food, respectively. For the studied agroecosystem models, the number of simulated crops for intercropping systems remains small. Spatial crop interactions are crop specific and their investigation is limited to a few common combinations due to their complexity and time needed to study these interactions through field experimentation. For temporal crop diversification at field or landscape scale, the number of available crops is higher with coverage of 10 to 70 crops depending on the model. In general, the number of available crops for simulation is higher for temperate and sub-tropical regions than those for tropical regions. There are fewer options for simulating less studied orphan crops, tuber and root crops, fodder crops, or newly introduced catch or cover crops as was also mentioned earlier (Kollas et al. 2015; Luedeling et al. 2016; Malezieux et al. 2009; Silva and Giller 2021), stressing the need to extend models for such crops.

4.2 Field classification into smaller units considering soil heterogeneities for site-specific management

Site-specific crop management can provide improved resource use efficiency, economic benefits and reduce environmental impacts (Basso et al. 2016; Kersebaum et al. 2002; Stadler et al. 2015). Agroecosystem models have the ability to simulate crop responses in heterogeneous fields with appropriate the input data, calibration procedures, and particular soil conditions. However, as models have limited skill in simulating effects of excess water, their performance is poorer under such conditions (Groh et al. 2020; Tewes et al. 2020b; Wallor et al. 2018). In precision agriculture, the term "management zones" is a popular approach for delineating fields into subunits for site-specific management to achieve increased resource use efficiency (Vrindts et al. 2005). An increasing number of methods are available for this approach as remote sensing technologies continue to evolve in their capabilities and availability for users. Site information that can be used for management zone delineation include geomorphology, soil chemical and physical data, soil classes, hydrological data, yield and biomass maps, crop coverage, and maps derived from proximal soil sensors. Statistical analyses for zone clustering are conducted to identify the optimal number of classification zones (Nawar et al. 2017). Additional factors relating to economic feasibility and machinery capability may be considered to define zone classes and size. Management zoning based on yield maps (Basso et al. 2011; Cammarano et al. 2020), multispectral images (Karydas et al. 2020), and soil proximal sensing (Davatgar et al. 2012; Peralta et al. 2015) have been previously explored in major cereal crops that are predominantly grown in sole stands to improve nutrient use efficiency. For diversified cropping systems at the landscape scale, Donat et al. (2022) applied a cluster analysis methodology using yield maps and proximal sensed soil characteristics to delineate "patch" units (~0.5 ha patch units, restricted to current machinery size) and classify patches into high and low yield potential zones, to design diversified cropping systems with smaller spatial arrangements to improve the agroecosystem functionality. The management zone concept can also be useful for diversified cropping systems through assigning crop species or cultivars according to the zone specification. For example, high yielding crop cultivars and species can be assigned to stable zones with optimum or close to optimum growing conditions. Zones prone to water stress, poor soil nutrient conditions, or salinity can be planted with tolerant crop cultivars or species or be assigned as biodiversity spots to improve overall field productivity and provisioning of ESS (Basso and Antle 2020).

At present, the minimum field size unit is restricted to machinery size. However, in the future, with the development of smaller and automated machinery, it may be possible to reduce field sizes without increasing labor costs, effectively redefining the scale of management zoning. However, the delineation of management zones based on small-scale heterogeneity of soil properties may be challenging for agroecosystem models and require inclusion of other soil-related processes relevant for crops under a large range of soil conditions. Vereecken et al. (2016) reviewed the capabilities of cropping system models with respect to their capabilities to simulate crop-related soil processes. They concluded that besides N, the simulation of the dynamics of other macro- and micronutrients in the soil is very limited in crop simulation models. Modelling of soil conditions that are unfavorable for crop growth like salinization (Webber et al. 2010), aluminum toxicity or water logging, and quantification of their impacts is currently limited. The simulation of some processes like water logging or shallow ground water may require extensive parametrization of hydraulic conductivity as well as the inclusion of two and three-dimensional soil water fluxes within the landscape.

4.3 Impact of diversified field arrangements on biotic stressors

Agroecosystem simulation models typically simulate crop dynamics based on environmental conditions and management practices (sowing, tillage, cultivar selection, fertilizer, and irrigation practices), without considering pest, disease, and weed damage (Ewert et al. 2015; Webber et al. 2019). Diversified cropping systems can reduce incidence through interrupting the respective pest life cycles, by providing food for beneficial insects in the field, and limited movement of pest from one crop to another. Break crops may differ in the extent to which they influence the populations of specific rhizosphere organisms, which may compete, antagonize, or suppress pathogens (Kirkegaard et al. 2008). The value of break crops will depend on the pathogen presence in particular cropping systems. Increase of soil organic matter and biological activity is reported to suppress soil-borne diseases, although inconsistent results hinder their practical application (Bonanomi et al. 2010). Tillage practices and residue management, e.g., mulching, affect soil water which in turn influence C and N dynamics as well as the survival of pests and soil pathogens. Modelling the effect of pests and diseases on plant growth and yield implies modelling (i) the causes of plant injuries (pest and disease life cycle) and (ii) the consequences of these injuries on crop performances to effectively link pests and disease damages relevant for understanding economic consequences (Esker et al. 2012). However, this is challenging to quantify in field experiments and include into agroecosystem models. Examples of common non-dynamic approaches for modelling pest damage to crops is the use of generic damage mechanisms (Boote et al. 1983; Rabbinge and Vereyken 1980), which were implemented in the DSSAT models for peanut and soybean leaf diseases (Batchelor et al. 1993; Boote et al. 1983), CERES for rice (Pinnschmidt et al. 1995), WHEATPEST (Willocquet et al. 2008), and recently in four other crop simulation models (HERMES, WOFOST_GT, SSM_WHEAT, DSSAT-NWheat; (Bregaglio et al. 2021; Ferreira et al. 2021) for wheat. Other examples linking agroecosystem models with pest and disease population models are the coupling of CERES-Rice to BLASTSIM, a rice leaf blast epidemic simulation model (Luo et al. 1997), using APSIM models coupled with the DYMEX population modelling platform to simulate the reduction of green leaf area due to leaf rust. The DYMEX platform can also be used to simulate weed and insect population dynamics (Whish et al. 2015). One of the few examples of pest and disease modeling for diversified cropping systems is reported by Poeydebat et al. (2016) who developed a generic process-based agroecosystem model including a pest and disease model to study diversified cropping systems including a three crop plant association to quantify pest regulations and yield tradeoffs. Donatelli et al. (2017) conducted a review on the current state of coupling pest and disease models with agroecosystem models and proposed a roadmap to improve their capabilities of simulating biotic stress. For this, they note that availability and quality of data observations for model input, model improvement, and evaluation are critical as is the establishment of a modelling community focused on pest and disease model development.

4.4 Agriculture 4.0

Agriculture 4.0 refers to the application of smart technologies based on Big Data, artificial intelligence, internet of things, cloud computing, and remote sensing, among others, to enhance production efficiency and promote agricultural practices for more sustainable and resilient agriculture (Rose and Chilvers 2018; Zhai et al. 2020). Combining agroecosystem models with smart technologies can further contribute to the improvement of model performance for the design and evaluation of the spatio-temporal dynamics of cropped fields. For instance, LAI data assimilation of field observations (Tewes et al. 2020a) or remotely sensed canopy state variables (Tewes et al. 2020b) into agroecosystem models can help to improve model performance. Remote sensing technologies can also help to further understand and estimate biotic (Dutta et al. 2008; Yuan et al. 2017) and abiotic stresses (De Canniere et al. 2021; Liu et al. 2019). The addition of soil property input data (soil texture, hydraulic properties), which can be challenging to physically collect in the field. This can be derived from proximal sensing technologies (Brogi et al. 2020; Wallor et al. 2019), and can help to better capture within-field heterogeneity as they may provide finer data resolution. Moreover, a combination of technologies such as artificial intelligence and machine learning can be applied to identify field heterogeneities and improve resource use, reduce environmental risks, and improve farm profitability (Hatfield et al. 2020). Although, there are still challenges to improve the robustness of new technologies in terms of available, accurate, ground truth data, model and user requirements (Dorigo et al. 2007; Hatfield et al. 2020), there is a great potential for them to contribute towards the design of multifunctional agricultural systems at farm and landscape scales (Asseng and Asche 2019; Basso and Antle 2020).

4.5 Ecosystem services and biodiversity

Depending on the model structure, agroecosystem models can dynamically simulate a diverse set of regulating and provisioning ESS, the most common are related to the provisioning of food, feed, fiber and fuel, the regulation of greenhouse gas emissions, water quality, and soil erosion. A strength of agroecosystem models is their flexibility to dynamically explore and quantify how the provision and regulation of ESS can be affected by specific crop management practices or climatic conditions, allowing the optimization of ESS delivery from agroecosystems. With the need to move towards multifunctional diversified agroecosystems, it is important to include biodiversity-related dynamics and additionally quantify their ESS (pest regulation, pollination, provision of functional botanical and fauna biodiversity). Regulation of ESS related to soil degradation processes are also important to consider, as not all models do. To study the impacts of crop diversification at the landscape scale, we propose a framework that combines both static frameworks and process-based models (Figure 2). In a first static step, the field is subdivided into management zones according to the physical and chemical characteristics. At the same time, the range of possible crops based on past crops and newly introduced crops is defined. Then, a range of crop arrangement scenarios can be defined and simulated with improved agroecosystem models. Post model evaluation evaluates the synergies and tradeoffs of the newly diversified crop arrangements, based on a set of criteria including the provision and regulation of ESS, resource use efficiency, and biodiversity, weighted as required by the relevant context. As current agroecosystem models are not fully capable of simulating or representing all processes, future model improvement is required. Considering soil heterogeneities in the framework can aid field arrangement design to improve resource use efficiency and assign areas with poor soil quality for biodiversity enhancement and conservation. This framework can serve as an exploratory tool for the design of field arrangements under the assumption that in the future small field robots will be able to manage fields with small, diversified patches (or management zones).

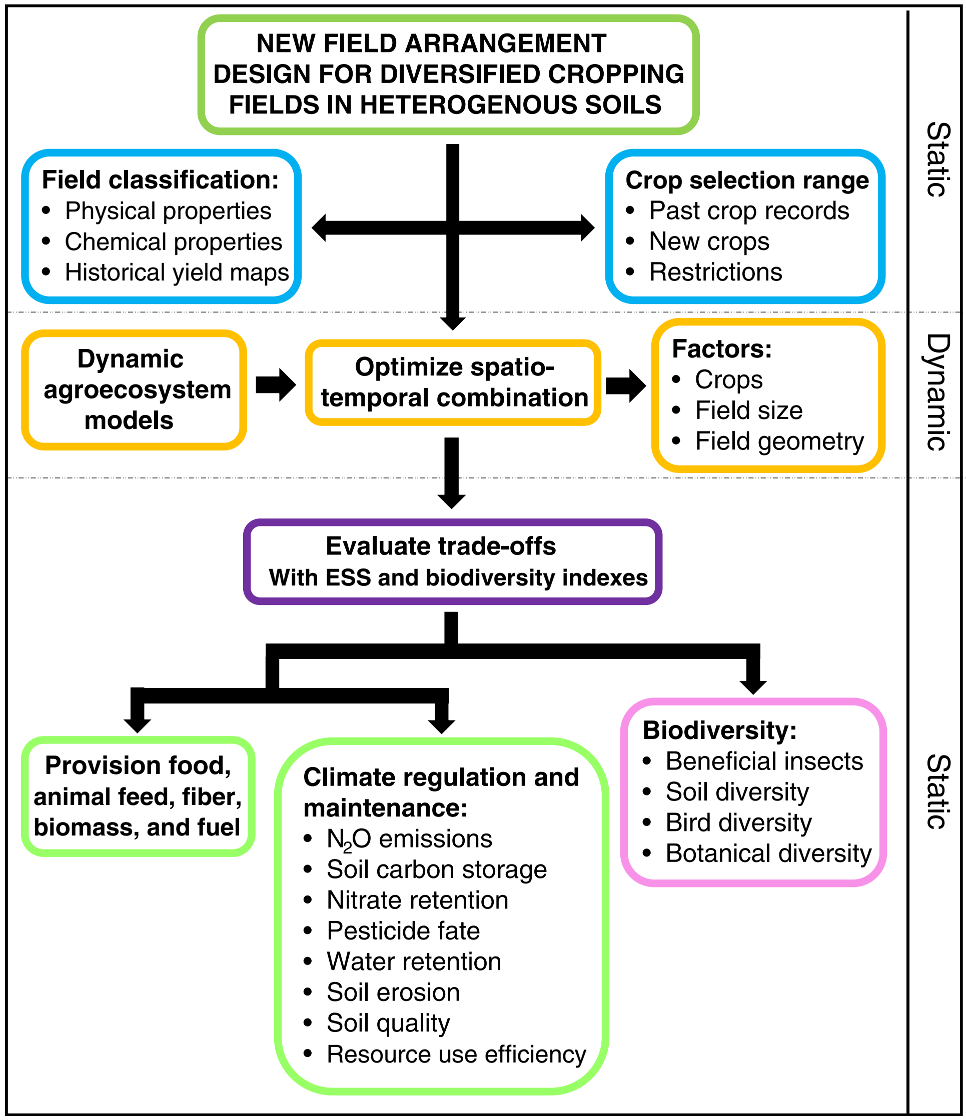

Fig. 2 Proposed framework for field arrangements design considering crop diversification within field with heterogenous soils. In a first step, the agricultural field is classified into different clusters (management zones) and a range of crops for the spatio-temporal crop diversification are selected (static step). The dynamic section includes the implementation of agroecosystem models to optimize the range of crops and rotations in diverse field arrangements. In a third static step, a post model evaluation is carried out for the selection of the best combination of crops and field arrangements given by a set of ESS and biodiversity parameters.

5 Concluding remarks

Previous agroecosystem model–based applications have primarily focused on crop growth and yield optimization, and to a lesser extent soil C and N dynamics, by simulating crop and soil processes as affected by management and weather variables without consideration of pest, weed, or disease limitation. With sustainability challenges in agriculture becoming even more critical, there is a need for assessments of new options for multifunctional diversified landscapes. For agroecosystem models to contribute to such assessments, there is an urgent need for improvements as well as their integration with other approaches and novel data sources to assess the provisioning of ESS and biodiversity. Agroecosystem models have been previously applied to explore spatial crop diversification at the field scale; however, limitations have been identified regarding the representation of crop interactions at the interface between strips or patches grown with different crops. In addition, simulation capabilities of above and below ground crop interactions are available for only few crop combinations, restricting their use to design diversified cropping systems. For temporal crop diversification, typically agroecosystem models can simulate a wide range of crop rotations as they include a variety of major sole crops, yet limitations exist for uncommon or newly introduced crops due to the lack of field observations required for model calibration and evaluation. The simulation of soil N- and C-related dynamics can be poor depending on model structure and calibration. With regard to the consideration of within-field heterogeneities, limited model applications were found for diversified cropping systems. However, examples can be drawn from sole cropping, where it has been demonstrated that agroecosystem models can simulate the effects of spatial heterogeneities on crops and some soil-related ESS. Uncertainties caused by model structure, calibration, and site-specific conditions are frequently reported. This suggests that a closer look is needed for the modelling of agroecosystem soil nutrient and water dynamics. Structural elements in the field such as hedgerows and flower strips are important sources of biodiversity in the field and can also affect crop yield and ESS by providing competitive and complementary interactions. Part of the resource competition can be modelled with agroforestry models, but lack of model flexibility when applied to different environments limits their application.

When moving to farm and landscape scale, decision-making frameworks and landscape generators are typically applied. Here, spatial diversification (landscape configuration and composition) is typically applied by using landscape generators, but cropland representation is rather simplified with no consideration for specific crop dynamics. Temporal crop diversification design is a static, rule-based process to optimize crop rotations based on agronomic, economic, social, or environmental indicators. Depending on the framework, common crop rotations for a particular area can be explored, but they may also have the flexibility to add new crops to the rotation set. Configuration within the farm would depend on soil characteristics and other pre-crop limitations but crop assignation is typically given to a whole field plot without further consideration of within-field heterogeneities. The smallest unit for crop diversification is also a field plot meaning that intercropping systems cannot be explored with these modelling frameworks. They are also limited on dynamically exploring climate, crop, and management interactions. Examples of combining static frameworks with agroecosystems models for the design and evaluation of temporal crop diversification were found, although the minimum scale of diversification is restricted to a field (i.e., a sole crop per field). To move towards a model-based platform for crop diversification design at field and landscape scale, we need to conduct further model improvements that additionally account for a more complex view of the agroecosystems including the addition of uncommon crops, further improvements for crop interactions when cultivated under intercropping, an external or internal processing framework for designation of management zones (by the use of field-collected or remote sensed data) that can be used for specific crop assignation, management and impact assessment of the practices on relevant ESS. Moreover, biodiversity and biotic stressor considerations need to be considered in agroecosystem modelling, but model improvements need to be linked to field experimentation that provides high-quality quantitative data to integrate into agroecosystem models. Biodiversity dynamics of plant and fauna diversity are widely studied in Landscape Ecology, and they can be an important source of information to improve and validate the agroecosystem models for a more integrated system approach. Remote sensing and field sensors can greatly contribute to the generation and collection of high-resolution input data. For example, for the generation of soil maps combining soil physical and chemical properties that serve as model input can be combined with air-borne records of spatio-temporal dynamics of crop canopy growth patterns for model calibration, validation, and improvement. Remote sensing can also serve to improve the understanding of environmental stress. Artificial intelligence and machine learning can further contribute to develop strategies to identify patterns of field heterogeneities and improve resource use, reduce environmental risks, and improve farm profitability. Diversified cropping systems that maximize provisioning and regulating ESS, resource use, economic and ecological tradeoffs are a promising alternative to intensive simplified crop production systems. Additionally, promoting the provision and regulation of ESS in agriculture may require policies that reward the benefits of ESS to compensate for the tradeoffs of high productivity versus increased ESS and farm biodiversity.

The consideration of causal relationships among system processes in process-based, dynamic models (in contrast to pure statistical input-output relations) allows to obtain a mechanistic understanding of the impacts of changes in boundary conditions (model inputs) on the outputs (e.g., crop yield, ESS delivery), which is the basis to develop demand tailored and sustainable management options. Thus, the complexity of a model is driven by the objectives of its end use (in our case understanding of bio-physical processes and their interactions in complex cropping systems). However, we are aware that there may be a trade-off between model complexity and the precision or accuracy in the outputs (Ahmad and Mahdi 2018). On the other hand, high-end observation and phenotyping methods for field and landscape experimentation (for example, within the platform of the PhenoRob project in Germany) offer a great opportunity to gather high-quality quantitative data to integrate into agroecosystem models and aid the model improvement process. Moreover, the implementation of finer degrees of crop diversification and smaller field arrangements is limited by machinery size, and a possible increase in economic costs as having more crops in a field can also imply more use of input resources such as energy and labor. Other issues such as soil compaction may arise due to increased traffic of heavy machinery, which can be also reduced with the use of smaller tractors and robotics that may be able to automatically handle the management of such systems and make the system more sustainable and profitable. It is important however to generate information and knowledge that contributes towards diversified cropping system planning. We propose a framework that combines static approaches and process-based models for the new field arrangements design. Different crop combinations can be assigned and combined with different spatial patterns depending on soil heterogeneities. The diverse crop-arrangement combination can be then optimized using an improved agroecosystem model. Model system evaluation can be conducted by identifying trade-offs and synergies based on criteria including the provision and regulation of ESS, resource use efficiency, and biodiversity. While there is an ongoing generation of data we emphasize, that it would be important in the future to explore the economic viability of the degrees of crop diversification by also evaluating the earnings from ESS and biodiversity in the field which may not have a direct economic return, but they influence the system. Modelling frameworks can be powerful tools that generate useful knowledge as they allow us to explore diverse combinations of crops, environments, and management practices that would otherwise be impossible through field experimentation. This in turn highlights the importance of continuing to address model limitations, which could be partly overcome through new technologies that can generate the data needed to support model improvements. With such advancements in mind, models have the potential to help us better explore the benefits of a diverse set of spatial and temporal crop diversification.

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