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Land use modelling needs to better account for multiple cropping to inform pathways for sustainable agriculture

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Multiple cropping, the simultaneous cultivation of several crops in space or time, is a global practice essential for intensifying and diversifying agriculture. Despite its substantial impact on environmental and socioeconomic outcomes of farming, multiple cropping is hardly accounted for in assessments of global food production, sustainability, and climate impacts. Such studies, often relying on modelling of cropping systems, land use change, and eventually the Earth system, are of growing importance in decision-making and policymaking. However, they primarily assume monocropping, neglecting carryover effects between crops and their implications for land use. This limitation compromises the representativeness of these studies and the conclusions they draw, essentially overlooking a substantial option space for sustainable intensification, nature-based solutions, and resulting land-atmosphere feedback. Herein, we outline the relevance of multiple cropping, reflect on its consideration in land-use models, and identify development requirements to enhance their inclusion in informing policymaking for sustainable food systems.

Persistently increasing demand for agricultural products is a key driver for the degradation of natural ecosystems through land conversion, the removal of trees, and emissions of agronomic inputs. During the second half of the 20th century, the industrialization of agricultural production resulted in increasingly homogenous cropping systems throughout large parts of the world, characterized by low crop diversity, high fertilizer inputs, extensive use of pest control agents, and often bare fallows outside the main cropping season[1–4]. Other farming systems - including small- to medium-scale, organic, agroecological, and subsistence agriculture – have, to varying degrees, continued to rely on diverse cropping practices such as crop rotations, agroforestry, and the co-cultivation of crops. These practices are broadly encompassed under the term multiple cropping (Table 1).

Substantial parts of global agricultural land are already under multiple cropping, which may increase even further in the future. Estimates for global cropland under double and triple cropping, cover cropping and agroforestry, respectively, are 12%, 10% and 20%[5–7], although precise data are scarce. Forms of multiple cropping are highly heterogeneous globally (Table 1) but regionally these systems may already be dominating (Fig. 1). In many countries, specialized systems exist with monocropping of key commercial crops such as sugarcane, maize, wheat, rice, or soybean grown for many years in a row, yet these are grown in rotation with other crops to avoid the depletion of soils and to manage pests and weeds[8].

Multiple cropping systems provide a range of benefits relating, for example, to pest control, efficient nutrient cycling, biodiversity, land productivity, and carbon storage[9,10], and are therefore a frequent element of nature-based solutions in agriculture[11,12]. Harnessing these benefits has, in recent decades, led to the promotion of multiple cropping systems in agricultural policies. Fostering the expansion of double cropping in Brazil for example, is estimated to have helped curb the expansion of soy and maize cropland by 30%, helping to spare millions of hectares of deforestation[13]. Policy incentives for cover cropping in the EU's Common Agricultural Policy have substantially contributed to controlling soil erosion and improving the climate regulation potential of soils[14,15].

Yet, depending on their implementation and local context, multiple cropping systems can pose additional pressures on both agricultural and natural ecosystems through exacerbation of soil disturbance, nutrient export, production costs, greenhouse gas emissions[16,17], and irrigation water requirements if the hydrologic regime is insufficient to support sequential crops[13,18]. In India, for example, the promotion of irrigated double cropping systems in the Indo-Gangetic plain has greatly contributed to food security

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Table 1 | Definition of major mono- and multiple cropping system categories considered herein, ranging from crop rotations to intercropping

Cropping system	Description and Examples	Alternative terms and Subtypes
No spatial or temporal overlap with other crops		
Monocropping	Cultivation of the same crop in succession annually without interruption by other crops such as continuous maize	Monoculture, continuous cropping ratooning (in sugarcane, for example), ratoon crop
Only spatial overlap, no temporal overlaps across multiple crops (partial or complete)		
Crop rotation	Cultivation of different crops across multiple years with single or multiple seasons per year	Sequence of crops from year to year, crop succession
Cover cropping	Cultivation of a crop typically not harvested outside the main cropping season. An example is the integration of legumes or grasses for soil health benefits and nutrient retention. May partly be harvested, e.g., for forage or grazed.	Catch crops, green manures
Sequential cropping	Cultivation of several crops per year in a sequence, most prominently rice-rice or rice-wheat systems in Southeast Asia or maize-soybean in South America.	Double cropping, triple cropping, sometimes referred to as rotation, if extending over several years
Spatial and temporal overlap across multiple crops (partial or complete)		
Intercropping	Simultaneous or overlapping cultivation of at least two crops on the same field. An example is maize-legume intercropping for improving soil nutrients.	Companion cropping, polyculture, crop association, subtypes with variations in spatial and temporal arrangements are relay, mixed, row, or strip intercropping. Includes “living mulches” as a synchronous form of cover cropping
Agroforestry	Cultivation of trees or shrubs around or within crop fields or pastures for a variety of ecosystem services, including production of crops, livestock feed, timber, or forage, soil protection, carbon storage, or microclimate moderation. Trees may or may not produce goods, e.g., fruit, cork, rubber. It can be a subtype of intercropping with trees or tree crops.	Silvoarable system (combinations of row crops and trees), orchard meadow, silvopastoral systems (combinations of grassland and trees), home gardens, parkland, live fence, tree intercropping, alley cropping, tree gardens, hedgerow intercropping, mixtures of plantation crops, windbreaks, shelterbelts

As there is no universally accepted definition of multiple cropping systems and their specific types, these definitions are provided as guidance here. They are grouped to fit the requirements of biophysical modelling, i.e., representation of temporal or spatial interactions among crops.

and sovereignty but the depletion of groundwater resources is expected to render the system unsustainable.

Socio-economic aspects of multiple cropping include its links to population growth, which increases pressure on land and demand for agricultural products – necessitating more intensive management,t including higher cropping intensity[19]. Other considerations involve rural employment, farm-level costs and returns and economic risks. Multiple cropping can for example pose productivity and economic risks through the competition of associated crops for resources and increase the risk of crop failures if the utilized suitable climate window is maximized[20].

Despite the prevalence of multiple cropping systems and the vast array of synergies and trade-offs they provide for ecosystem services, we have observed that, to date, they have received minimal consideration in global land use modelling studies. Large-scale agricultural and land use modelling, mostly performed with global gridded crop models, and agro-economic land use models have almost exclusively assumed monocropping systems with their distinct agro-environmental processes (Fig. 2). Consequently, studies based on such modelling systems are limited in the option space considered in policy evaluation and can typically only provide recommendations for agricultural pathways within the boundaries of common intensification systems.

Here, we begin by outlining the significance of multiple cropping systems in the context of land-climate interaction, land productivity and food production and the associated environmental and socioeconomic outcomes. This is achieved through a comprehensive review of the primary biophysical and climatological processes influenced by the presence of multiple cropping and addressing remaining gaps in our understanding of these processes. Thereafter, we summarize recent developments and limitations in the modelling of multiple cropping within the three main categories of global models of land use: crop models, including global gridded crop models, agro-economic models, including integrated assessment models, and Earth system models, including land surface models. In doing so, we include a wide range of multiple cropping systems, from intercropping and agroforestry to rotations, sequential cropping, and cover cropping,g which are then contrasted to monocropping. Throughout this discussion, we explore model data requirements essential for implementing multiple cropping, highlighting persistent limitations in data availability, and proposing innovative ideas for data collection and synthesis. We conclude by identifying both short- and long-term options to incorporate the diversity of multiple cropping systems into future agricultural and food assessments, contributing to pathways towards sustainability.

Multiple cropping and climate

Land-climate interactions in multiple cropping systems

Atmospheric and terrestrial land surface processes are intrinsically coupled, as changes in climate and vegetation dynamics affect each other. Changes in land management can exhibit similar consequences for climate as changes in land use type[21] but are less well understood.

Evapotranspiration is one of the central fluxes that define land-atmosphere interactions[22]. In agricultural areas, the water balance is strongly affected by crop management practices such as crop choice, duration of the cropping season, irrigation intervals, and fertilizer applications[23,24]. Annual evapotranspiration in double cropping systems is higher than in single cropping systems[25] because of a longer growing period (Fig. 2). If supplemental irrigation is used, this can lead to an irrigation cooling effect, altered monsoon rainfall[26] and groundwater depletion[18,27].

Similarly, higher evapotranspiration per land area is often observed in agroforestry systems due to higher transpiration by trees with perennial growth compared to sole crops. In both double cropping and agroforestry - as well as other forms of multiple cropping - the water balance of the main crop can be improved. This may occur through mechanisms such as shading, which reduces atmospheric water demand, or enhanced infiltration, which increases water availability. These effects depend on agro-environmental conditions, the combination of plant species, and specific in-situ management practices[28,29].

Specific combinations of crops in space and time and the resulting duration of plant soil cover also alter land surface conditions, such as surface air temperatures[30] (Fig. 2), affecting local and regional climate. In general, we

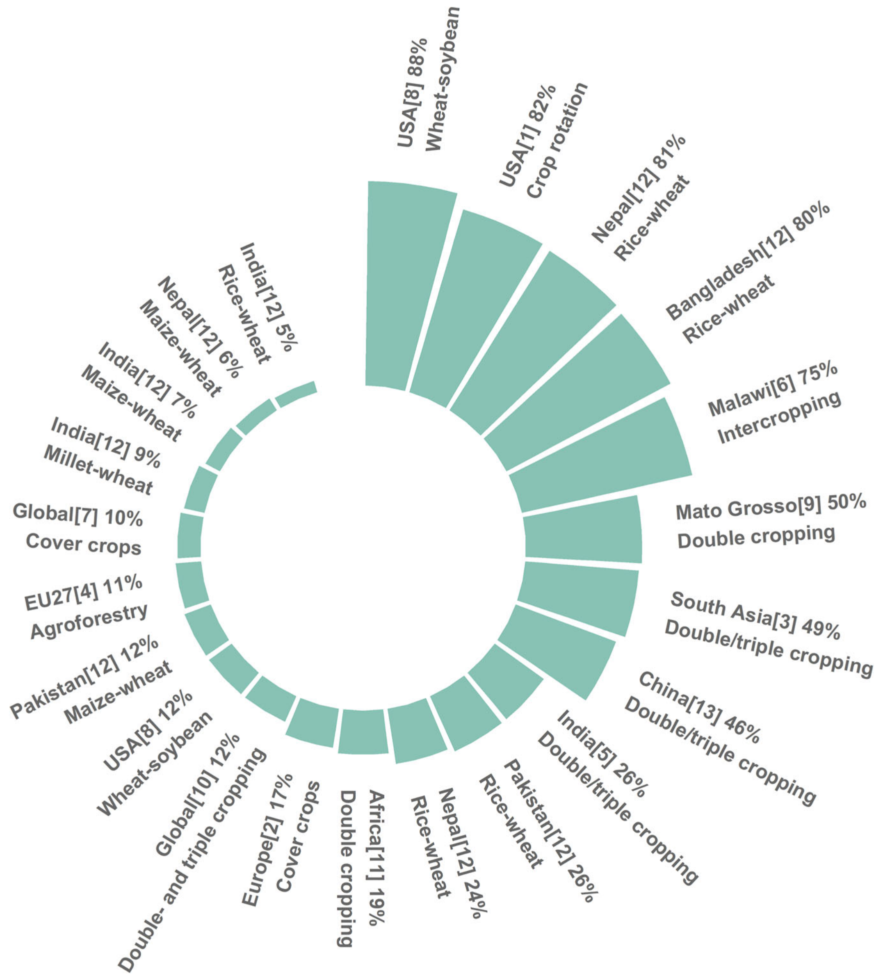

Fig. 1 | Estimates of area shares for various types of multiple cropping in selected countries and world regions. Barplot height is relative to the percent multiple cropping area of total cropland, arable land, or agricultural land, except for [8] and some values for [12], which is relative to the national wheat area, and [2], which is relative to cropland without winter crops. The figure only shows selected data points for brevity, but the underlying data table extends to fifty-seven data point[173]. Sources: [1] Padgitt et al.[174], [2] Eurostat 2016, Agri-environmental indicator - soil cover, [3] Gumma et al.[175], [4] Mosquera-Losada et al.[176], [5] NRCP[177], [6] Own analysis, see (Supplementary Note 1, Fig. S1), [7] Poeplau & Don[6], [8] Seifert & Lobell[40], [9] Spera et al.[168], [10] Waha et al.[7], [11] Xiong et al.[178], [12] Yadvinder-Singh et al.[179], [13] Zuo et al.[180].

expect a cooling effect from double cropping as it increases the vegetation period, but bare soil conditions between the first crop's harvest and the second crop's planting can lead to the opposite effect. In the summer maize-winter wheat double cropping system of the North China Plain, for example, surface air temperatures during the June fallow period were higher in double cropping compared to single cropping regions with continuous soil cover, which was attributed to reduced evapotranspiration on June[30,31].

Changes in albedo under different cropping systems (Fig. 2) have been studied mostly for cover cropping and crop rotations, which increase albedo by covering bare soil, thus reducing warming[29]. Over Europe, for example, planting cover crops on 4% of the land for three months per year would increase the surface albedo and reduce radiative forcing with a long-term average mitigation potential of 2.9–3.2 Tg CO_2 per year[32].

Besides the above fluxes, atmospheric greenhouse gas concentrations and most prominently atmospheric carbon dioxide concentrations are influenced by land and crop management practices. Due to their sizeable potential for carbon sequestration in agriculture-dominated landscapes, cover crops and agroforestry have been proposed as nature-based solutions for land-based carbon storage[5,6,33]. The potential for increasing soil organic carbon storage on global cropland by shifting from current management to cover crops, green manure, or other residue return practices has been estimated at 0.28 Pg C yr^{-1} [34]. The physical potential for carbon storage in agroforestry was estimated as 0.13–0.93 Pg C yr^{-1} [11,12]. In these studies, the definition of suitable areas for agroforestry and sequestration rates was subject to a range of assumptions, including the likelihood of adoption or the co-benefits if implemented on degraded land, and must therefore be considered both conservative and highly uncertain, as were the literature-based assumptions on carbon sequestration rates. The potentially large climate mitigation benefits of cover crops are increasingly contested due to contradictory outcomes between field records and potential adverse impacts on crop yields affecting the net carbon balance[35]. Conversely, increases in fertilizer inputs, fuel for machinery, and even more so additional seasons cultivated with paddy rice can exacerbate greenhouse gas emissions at higher cropping intensity.

Climate change impacts on multiple cropping

Climate influences the cropping frequency and the crop growth duration[36–38] through changes in phenology and growing conditions, and exerts distinct seasonal impacts on crops[39]. Warming could, for example, increase opportunities for double cropping in the northern hemisphere[40,41]. It is, however, unclear how single cropping transitions to double cropping, even if the suitable areas increase and if economic incentives and enabling factors exist for farmers to make use of such opportunities[42]. Conversely, warming and changing rainfall patterns could restrict options for multiple cropping. The second crop´s feasibility might decrease where the first crop´s sowing is delayed and its cycle extended[43] and there are further season-specific limitations such as drought and heat[20,44]. Overall, it is possible that benefits from increased cropping frequency would be offset by climate-driven yield decreases. Global estimates show an overall net reduction in cropping frequency as increases in cooler regions are offset by larger decreases in warmer regions[45]. It is increasingly recognized that climate impact assessments based on crop yield alone may introduce systematic biases and hence need to be expanded to consider changes in land use and cropland[46].

For many multiple cropping systems, it remains unclear how sensitive they are to unusual weather years and climate change and to what extent they affect climate risk. Crop diversification, for example, can improve

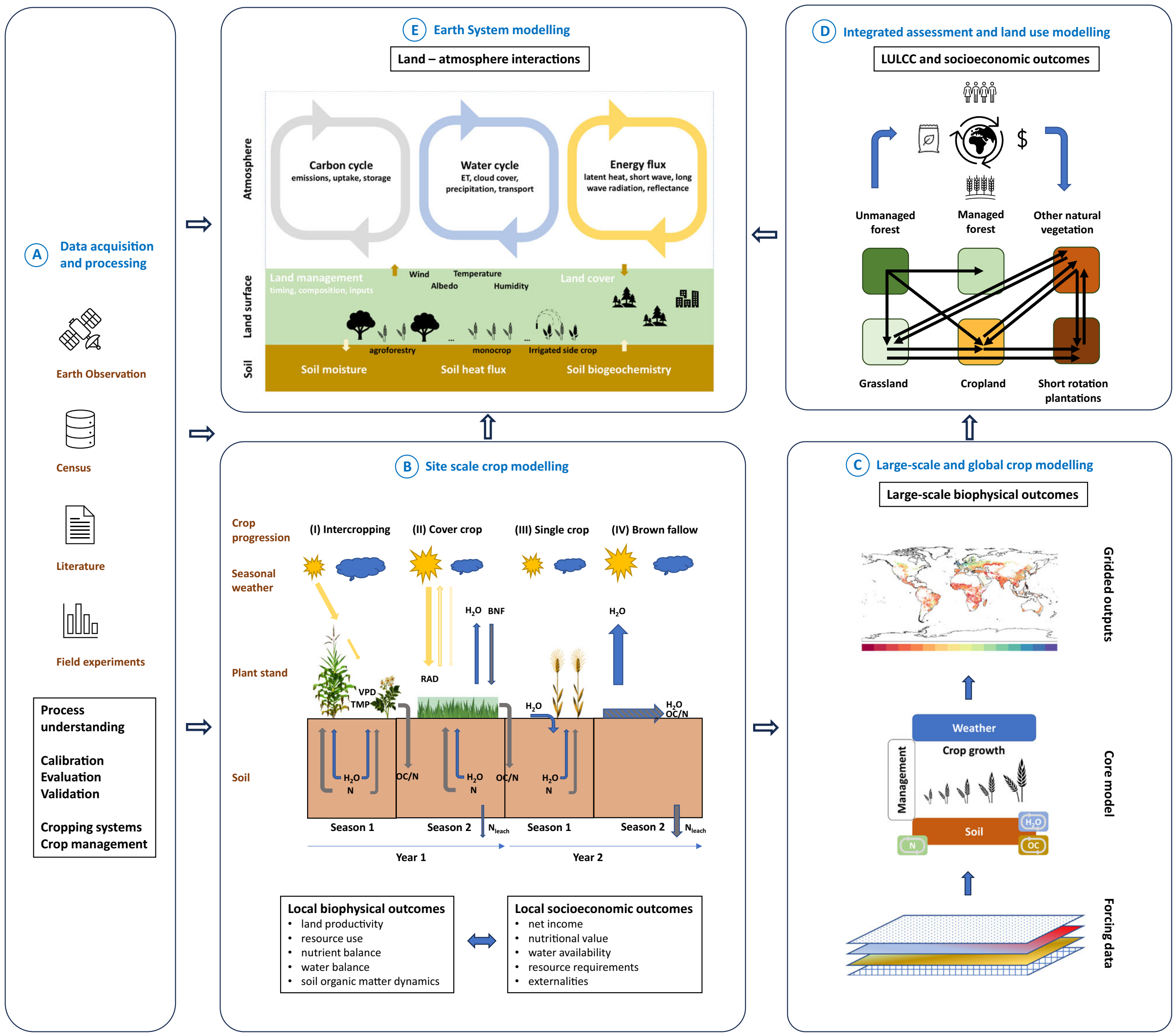

Fig. 2 | Schematic of the data acquisition and modelling chain for assessing multiple cropping systems concerning their biophysical, socio-economic, and Earth System outcomes. Each panel is elaborated in a subsection of this paper. **A** Data acquisition via remote sensing, census, literature, and experimentation to derive extent, management, biophysical processes, and economic outcomes that serve as a basis for all subsequent modelling types. **B** Biophysical simulation of multiple cropping systems at the site or pixel scale for an exemplary rotation excerpt (I-IV) with selected interactions and carry-over effects) and associated (socioeconomic) outcomes. **C** The same simulation and outcome quantification embedded in a large-scale to global simulation framework. **D** Integrated assessment of socioeconomic land use outcomes. **E** Earth System modelling, including effects of multiple cropping on land cover and land use changes besides endogenous simulation of cropping systems and land-atmosphere interactions. Arrows between panels indicate flows of data or process representation. RAD radiation, N nitrogen, OC/N organic carbon and nitrogen, BNF biological N fixation, TMP temperature, VPD vapour pressure deficit. Brown fallow is a period of bare soil.

economic resilience to price fluctuations and climate shocks as a kind of insurance but requires additional investments that may result in net losses. Also, cultivating multiple crops when climatic risks are expected over the entire growing season may lead to higher losses overall. Agroforestry is often promoted as an adaptation of row crops to an adverse climate. Yet, it remains unclear under which conditions such benefits can be realized[28]. Also, for tropical agroforestry systems, a recent review points to concerns about reduced tree growth, intensifying tree-crop resource competition and reduced crop yields[47].

Multiple cropping, land productivity and implications for socio-economic development

Land productivity and food security

Multiple cropping has been promoted as a strategy to increase productivity, and indirectly, income and food security. This is based on increases in cropping frequency[13], allowing more biomass to be produced on the same land, beneficial biological interactions between crops, and improved resource use efficiency that affect land productivity overall. It is unclear how much food is currently produced on land under multiple cropping, but between ten and twenty percent of growth in crop production since 1961 is estimated to come from increases in cropping intensity globally[48,49]. As a co-benefit, increases in land productivity might reduce the need for further cropland expansion[7,19,50] but this is contested due to potential rebound effects increasing land use because of efficiency gains[51]. Cropping intensity has also increased as a reaction to increased food demand[52], including for livestock products[53], labour demand and availability and to efforts increasing national sovereignty for staple foods.

Intercropping is widespread in traditional cropping systems, as it allows for intensification of systems that are low in nutrients and soil organic matter[54] and can confer additional benefits for pest management, erosion control, and land use[55,56] In low-input systems of sub-Saharan Africa, intercropping increased crop yields by 23% to 40%[54,55] A global review found an average increase for grain yield in intercropping of 23% as well and a higher protein yield, but a slight yield penalty of −4% for the most productive single crop[57]. The above impacts, however, differ strongly with the crop type and crop management[55].

Cover crops can strongly affect yields of the primary crop depending on whether leguminous, non-leguminous, or mixed cover crops are used and other management characteristics such as fertilizer use and the timing of cover crop termination[58–60]. The use of nitrogen-fixing cover crops as "green manures" can enhance crop yields in smallholder systems, especially in sub-Saharan Africa, if combined with integrated soil fertility management but may compete with a second food crop[61]. Growing crops in rotation can increase yields by up to 20% on average compared to monocropping, with the effect being higher for legume-based rotations and in the first year of the rotation[62].

Land productivity and profitability might be constrained by the availability and cost of labour in a field or farming system with multiple crops and the complexity and added costs of managing a diverse system[56,63,64]. This is, however, debated as a recent global meta-analysis showed that diversified systems are as profitable as monocultures[65].

There are positive associations between crop diversity in agricultural systems and dietary diversity[66,67] and crop diversity and anthropometric measurements[68,69]. A recent review found that agricultural diversity had a positive effect on food security in two-thirds of all reviewed cases[70]. This effect might be limited to certain parts of the year and the consumption of certain crops[71]. An important role in dietary diversity has been attributed to agroforestry systems[72] as especially tree crops such as fruits and nuts are frequently lacking in many food insecure regions[73].

Environmental aspects and sustainability

Multiple cropping systems can improve or degrade environmental outcomes of crop production depending on the type of management and cropping system, which influence resource use. There are key differences between synchronous (e.g., intercropping) and asynchronous (e.g., double cropping) multiple cropping systems due to the time lag between growing cycles that influences biogeochemical cycling, hydrology, and resource competition The main environmental considerations associated with multiple cropping involve nitrogen and water use, pesticide inputs, and the potential to reduce cropland expansion as discussed in the previous section.

Incorporating legumes or nitrogen-fixing trees can lower the nitrogen requirement through a transfer of residual fixed nitrogen to a following crop[29,74,75] (Fig. 2). Cover crops typically decrease nitrogen leaching through uptake but may temporarily render nutrients unavailable to a main crop[58,76] (Fig. 2). A strategy to minimize competition between co-cultivated crops is via crop selection based on root architectural traits, i.e., combining shallow and deep rooting crops like in agroforestry, and a range of field management practices including tailored tillage and fertilization regimes[77,78].

An important consideration for environmental sustainability is the potential increase in the demand for irrigation water. Over 60% of all double and triple cropping systems, for example, have a season requiring supplemental irrigation, which can cause depletion of water resources, as seen for example, in the Indo-Gangetic Plains[18]. Again, water use strongly depends on management, location and crop choice. Sustainable use of water resources and precision irrigation can provide both environmentally and economically viable outcomes[79]. Residual soil humidity after a crop grown during the monsoon season can be used as a starter for the following dry season crop with optimal timing[80]. For tree-crop combinations, there might be trade-offs between the higher water demand of trees and beneficial effects through shading, improved runoff infiltration, and wind shelter[28,72], although the underlying processes are still under investigation[28] and trees can as well improve water availability, e.g., through hydraulic lift[81]. Irrigation water demand can be reduced in systems with a cover crop that stabilizes soil structure[82], enhances infiltration, soil water capacity and soil cover if competition for water with a main crop is avoided[60].

Intercropping is an important practice for integrated pest management because as the right combination of "repellent" and "attractive trap" plants can allow the behaviour of insect pests and their natural enemies to be manipulated to reduce pest damage[83]. Such "push-pull" strategies reduce the need for chemical or biological control, reducing pesticide and use, and the risk of insecticide resistance, but to be beneficial, they require a good knowledge of the relevant host-pest interactions[84].

Beyond in-situ interactions, multiple cropping systems - particularly those of higher complexity such as agroforestry - are often deeply embedded within broader landscape dynamics. These systems offer high multifunctionality, serving as wildlife habitats, sources of income, and expressions of cultural identity. However, due to intricate socio-ecological relationships, they can either enhance resilience or increase vulnerability, especially when a key component is disproportionately affected. These outcomes depend heavily on the local context and the specific system in place[85].

State-of-the-art and challenges in modelling multiple cropping systems

Representation in crop models

Cropping systems models, herein defined as models that simulate major crop types and their management practices, and their large-scale implementations in global gridded crop models, have become state-of-the-art tools for climate impact estimation and the evaluation of crop management scenarios[86–88]. They can also quantify externalities of contrasting production methods[89,90], feed continuously into the development of cropland components of hydrologic[91] and Earth System models[92], and provide inputs for integrated land use models (see below).

Asynchronous sequential systems and their biogeochemical fluxes (Fig. 2) have been included in cropping models for several decades with varying degrees of detail[93] and have been evaluated for various target regions and scales (Supplementary Material, Table S2).

When crop sequences cannot be simulated directly, modelling individual crops can still provide insights into seasonal, climate-driven productivity and resource needs. However, this approach overlooks carry-over effects - how previous-season management, crop-soil interactions, and environmental conditions influence the growth and yield of subsequent crops.

The complexity of synchronous systems such as intercropping can be simulated by only a few models (Supplementary Material, Table S2). Most of these are limited to interactions between crops regarding resource sharing, assuming a homogenous mix of combined crops. Plasticity of plant responses, such as root distribution, leaf area index, or crop height may be partially considered. Only STICS appears to have an intercropping implementation for specific field designs[94] while agroforestry has so far solely been implemented in the APSIM model[95,96]. While there is a range of specialized agroforestry models[97–99] these have been tested for specific climate regions only and lack detailed representations of row crops. A combination of outputs from specialized models, such as agroforestry models for tree crop plantations and row crops from cropping systems models is feasible but requires consistency in describing sub-processes such as water and nutrient fluxes. Specialized models for single plants are increasingly addressing ecophysiological interactions in more detail[94,100] but are typically specialized in terms of plant parts (e.g., root system), species, and interactions (e.g., Fig. 2), require comprehensive parameterization, and do not consider crop management, limiting their applicability in land use modelling. Still, coupled with crop models, such approaches show promise for accurately representing competition and facilitation processes in agroforestry systems[101].

Simulation of biological interactions mostly use simplified pest and disease damage functions[102] that seldom involve mechanistic coupling of models[103]. A key limitation is understanding of the actual interaction at a process level and its generalization[104], e.g., between microbes and plants or insects and plants. Soil microbiology is foremost represented in static soil organic matter turnover coefficients[105], albeit recent developments in soil microbial modelling[106] could inform improvements in dynamic community composition.

Upscaling in large-scale and global gridded crop models

The upscaling of multiple cropping systems in crop model simulations requires skilled core models, i.e., field-scale models or dedicated routines, and sufficient data on cropping systems distributions, their management, and reference data for calibration and evaluation at larger scales.

Crop management data available at global scales are limited to nutrient inputs, irrigation and growing seasons whereas other management information is missing[107,108] - except for crop calendars in distinct rice seasons[109]. Therefore, crop rotations and sequential cropping have not been studied globally, but have mainly been implemented in regional pilots[90,110–116]. Such studies have demonstrated that model performance can substantially be improved in world regions dominated by such systems[117] and that growing season adaptation to climate change varies depending on whether or not double cropping is considered[116]. The only multiple cropping system simulated on global scales is cover cropping, but without a validated baseline[33,89]. Synchronous systems have not been simulated globally[33,89,90,110–117].

Any management practice should first be tested, evaluated and modelled at the field scale. Then, upscaling, aggregation, and generalization to regional, national, or global levels can support agricultural policy-making and align with broader global challenges such as climate change and biodiversity loss. However, this process may delay implementation, as practices must demonstrate relevance across diverse locations or larger areas.

Agro-economic and integrated land use models

While biophysical or process-based models offer insights into cropping system outcomes, land use patterns and pathways are derived through agro-economic models, such as partial equilibrium models and integrated land use models, which balance supply and demand, considering also policies or economic constraints[118]. If coupled to biophysical and crop models, these frameworks more accurately represent land-use change and help establish links between demand for agricultural products and land use dynamics. This integration also enables the representation of diverse crop management strategies and their outcomes[119] or their aggregation to simulate broader trends in agricultural intensification[120]. Such models typically represent cropland in terms of physical rather than harvested areas and consider the average productivity and demand without capturing seasonal variability.

Being dependent on outputs from biological and crop models, integrated land use models rely on upstream improvements in the representation of multiple cropping systems, but simultaneously require improved representation of the socioeconomic factors driving land use decision-making. As simplified approaches, cropping intensity factors have been applied to converge consistency among harvested and physical areas[121], and crops have been combined from simulations of individual crops[122], in both cases without considering specific seasons.

This approach is appropriate as a simplification if it is irrelevant why cropping intensity is low or high, or is changing spatially or temporally, or the model is not sensitive much to such changes. The same level of cropping intensity can have many different economic and environmental outcomes as it is only a representation of the number of harvests per year or per area. This simplification is also appropriate if there is no need to simulate the historical development or scenarios of individual land management changes, including shifts from single to double cropping or mono- to diversified cropping or crop only to tree-crop systems.

Land surface and Earth System Modelling

Land surface and Earth system models usually employ simple representations of cropping systems[92,123,124], with just a few models[92] representing land management in terms of crop harvest and residue management and use of fertilizer and irrigation. This is related to the historically strong focus on representing land use change and the global carbon and water cycles more broadly. More recently, the focus has started to extend towards considering land management, as more datasets on the global scale are developed. Sequential cropping has solely been implemented and evaluated offline (i.e., using the land system model only, forced with climate data) at field and regional scales[125,126]. Alternatively, generic C3- and C4-type crops may be simulated throughout the year and harvested according to maturity rules[127,128], which essentially mimic single, double, and triple cropping wherever a practice is suitable. However, this approach ignores differences among crops, which are vital for informing how multiple cropping systems may respond to a changing climate. A fully coupled setup has been used to simulate effects of cover crops on albedo and regional climate[129] but was challenged for its underlying assumptions[130].

Data requirements and availability for large-scale land use modelling

The modelling of multiple cropping systems requires a range of input, calibration and validation data. Besides data on climate, soil, and topography required in any biophysical modelling, these include data on crop management such as growing seasons, crop specifications such as crop type and variety, and geographic location and area for specific multiple cropping production systems.

Methods for large-scale mapping of multiple cropping production systems are the most advanced for sequential cropping and crop rotations, as evidenced by multiple methods developed and datasets available on different scales. One limitation of remote sensing in this context is that it requires ground data and expert knowledge of crop management to be successful[131], which questions the potential of validating and applying such methods at a large scale. On local to national scales, medium resolution satellite imagery can be aligned with vegetation indices indicating typical crop cycles[132–135]. Another approach is to combine separate land use classifications for the wet and the dry season, which indicates the potential for sequential cropping systems[136], but typically there are considerable data gaps for the wet season in tropical agriculture. For the US, the US Department of Agriculture produces the cropland data layer CropScape[137], including layers for double cropping of wheat, soybean, corn, cotton, other cereals, and lettuce, which are almost directly usable crop model inputs. The only map of crop rotations to our knowledge is on the local scale and identifies currently used crop rotations mapped over eight years based on multitemporal crop type mapping in Germany[138]. Although not directly indicating the physical area of each crop rotation, other methods can indicate dominant crop rotations[139,140], transition periods, and areas with consistent multi-year rotations[141]. Alternatively, systematic reviews and expert and grower consultations can help identify the most important crop rotations[8,142–145].

National to global scale crop calendars and phenological observations are available from remote sensing, agricultural surveys, and integrated approaches[109,146–150]. Integrated approaches combine remote sensing and ground census to disaggregate crop area into specific double and triple cropping systems area[151,152]. A similar approach led to the development of global, spatially explicit maps of individual double and triple cropping systems[7]. Crop calendars are, however, often only available for one point in time and are not updated regularly. Consequently, global datasets are only available for around the year 2000. Data collection on global scales is often more expensive, takes longer, and requires syntheses, which typically leads to a delay of five to twenty years in producing such datasets.

There have been a few attempts to map agroforestry, intercropping[153] and cover crops[154,155]. There is currently no global map of actual agroforestry areas, but suitability for agroforestry has been mapped globally[156], and regionally[157,158]. The mapping of tree crops and shrubs typically used in agroforestry systems, the application of forest-related methodologies to agroforestry systems, and the mapping of individual trees outside of forests are promising next steps[159–161]. A main challenge for mapping synchronous multiple cropping systems is to establish the degree of actual overlap of crops at a given location, rather than simply a spatial co-existence on an aggregated spatial scale. Other relevant methods for data collection on multiple cropping include identifying potentially suitable areas for multiple cropping based on soil and climate and describe average cropping frequency and cropping intensity (see Supplementary Note 2).

For model calibration and evaluation, priority variables typically are crop yield, phenology, evapotranspiration, leaf area, and aboveground biomass[116,125]. Data availability and quality depend on the scale the model operates on, with data availability for field-scale modelling typically being very good. Global crop yield records for all crops cultivated worldwide are available (albeit with varying quality) as national average yields in the FAO statistical database[162] and as gridded datasets for maize, rice, wheat, and soybean[163–166]. Season-specific yield or production records are only becoming available for selected regions and at aggregated district-level[13,116] whereas annual global gridded crop yield and production maps have been readily available for more than a decade[166,167].

Beyond the challenge of achieving spatial coverage, it remains very difficult to generate multi-year datasets to detect temporal trends and persistence in multiple cropping areas[64,168] and understand its drivers.

Towards an improved representation of multiple cropping in land use modelling

The preceding sections highlight a range of agro-environmental and socio-economic processes associated with multiple cropping systems. Most of the model types reviewed possess basic capabilities to represent multiple cropping. However, several key processes remain either partially addressed or entirely absent in current land-use models. These include, for example, carry-over effects between seasons, biological above- and below-ground plant interactions, and microclimates in synchronous multiple cropping systems (Table 2, Fig. 3). A common approach to cropping system model development in this case is to adopt routines from specialized models, which exist for many of these processes in multiple cropping systems (Supplementary Material, Table S2).

We propose further priorities for model development and identify opportunities for upscaling and global integration that are likely to be most impactful in the near future (Table 2, Fig. 3). We see these activities as having the potential to decrease model error, increase the applicability of models and deliver the largest value compared to the difficulties and complexity of the implementation task. Model improvement may be handled by individual research teams or coordinated by larger community efforts such as the Agricultural Model Intercomparison and Improvement Project (e.g. Jägermeyr et al.[87]) that aims to improve, apply and connect models to take on current and future challenges in sustainable food systems.

Ultimately, these efforts aim to address the core question of the role that multiple cropping systems currently play – and can potentially play - in ensuring sustainable food security now and in the future (Fig. 3). In our view, the research themes emerging from this central question need to be given greater attention if we are to advance the development of land-use models that adequately reflect the cropping systems dominating large areas of global cropland.

We assume that current estimates of impacts of climate change, adaptation, and mitigation suffer from inherent biases due to the insufficient consideration of multiple cropping. One way forward to strengthening modelled responses lies in the production of data on the diverse spectrum of multiple cropping types, their geographical extent and spatial distribution, and the associated management practices. Multidisciplinary approaches between data providers and data users are required to accelerate the readiness of the modelling sector to include multiple cropping systems.

Suggested priorities for data collection and syntheses to support the modelling of multiple cropping systems are:

- Targeted input data: Focus on providing crop-, system-, and season-specific input, validation, and calibration data, for example, from agronomy trials, census or remote sensing.
- Remote sensing fusion: Develop integrated remote sensing approaches, for example, combine crop calendars with vegetation greenness patterns to identify trends in crop seasonality.
- Seasonal yield surveys: Encourage national surveys to distinguish between crop yields in different cropping systems and seasons, for example, rice yield in the monsoon versus the dry season, maize yield in maize-soybean versus sole crop systems.
- Land-use mapping: Develop multi-year land use and crop type classifications for mapping crop rotations and cover cropping.
- Crowdsourced data: Explore citizen science and crowdsourcing of data in addition to more traditional data collection methods.
- Cropping constraints: Focus on data on factors directly or indirectly limiting or enabling multiple cropping, such as agricultural labour productivity and types of agriculture and farming systems.
- Strategic data alignment: Increase awareness and knowledge on data requirements for land use modelling in data-related disciplines such as remote sensing or in institutional settings involved in the census of crop production.

By prioritizing the collection of detailed, georeferenced data on key multiple cropping dynamics, we can improve the accuracy of our estimates and, in turn, better inform strategies for sustainable food systems, as well as

Table 2 | Key challenges and opportunities for improving the representation of multiple cropping in land use modelling

Challenge	Status/Ways forward
Quantify effects of biogeochemical carryover (organic matter, nutrient cycling, soil hydrology) among crops over time	Can already be done in some crop models[169]
Biogeochemical exchange among synchronous crops	Some models with homogenous mixtures of crops; first pioneers with 2-3D field design[170,171]
Within-stand microclimate in agroforestry systems	Competition for light is included in several crop models; first pioneers with other climate quantities; still comprehensive lack of process understanding for generalization[28,99,170]
More complex models to inform the structure and parameterization of the simpler model, or used together with simpler models in multi-scale approaches.	Specialized modelling approaches exist, e.g., for allelopathy and agroforestry; No demonstration of link to simpler models yet[97–99,172]
Overcome gaps in input (i.e., large-scale growing seasons, crop and systems distributions, seasonal management), calibration (regionally representative plots or sufficiently extensive databases on diagnostic variables), and validation (large-scale seasonal crop productivity) data. Formulate priorities for data collection and synthesis.	Regional pilots to demonstrate potential of selected methods; Global spatial explicit datasets for selected components of multiple cropping, but not updated regularly[110,116,117]
Simulate biogeochemical cycling, crop productivity, and resource use in multiple cropping systems using global gridded crop models where data availability is largest (e.g., sequential cropping and crop rotations)	Basic, global macro-regional crop rotations have been estimated by Barbieri et al.[8], global patterns of sequential cropping by Waha et al.[7], which may also serve for deriving growing seasons; no data on synchronous systems available
Implement economic drivers of multiple cropping decision-making (seasonal prices and returns) and sound rules for combining crops	Requires integration with farm / land use economic model; one prototype for soybean-maize double-cropping in Brazil[122]
Manage the increased complexity of processes, computational load and competing priorities for model development	Requires strategic planning of model development needs and decisions on the level of detail in which multiple cropping is to be considered

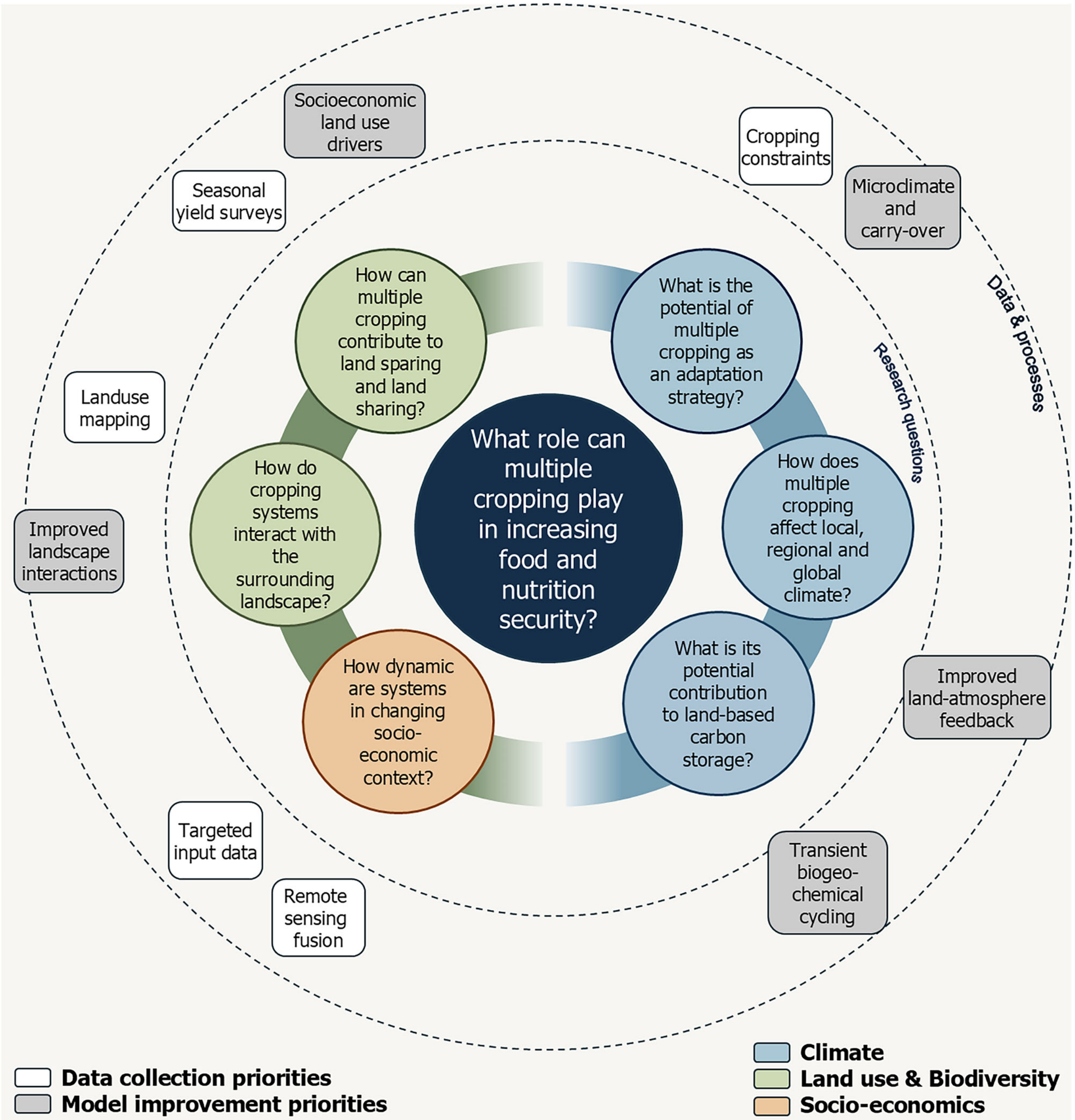

Fig. 3 | Data collection and model improvement priorities for key research themes associated with multiple cropping and its representation in land use models. Graphical overview of data and model implementation priorities (outer circle) required to answer specific research questions (inner circle) on climate (blue), land use and biodiversity (green) and socio-economic considerations (orange) which ultimately help to evaluate the contribution of multiple cropping systems to sustainable food and nutrition security (centre).

climate change adaptation and mitigation. This undertaking is imperative for fostering a more nuanced and scientifically grounded approach to address the complexities of multiple cropping within the context of global food systems.

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
The data that was collected for use in this manuscript are openly available: Waha, K. & Folberth, C. Multiple cropping area estimate by region and country. Figshare. Dataset. (2024). https://doi.org/10.6084/m9.figshare.25225829.

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