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Representing responses to climate change in spatial land system models

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Abstract

Modelling future change to land use and land cover is done as part of many local and global scenario environmental assessments. Nevertheless, there are still considerable challenges related to simulating land-use responses to climate change. Mostly, climate change is considered by changing the temperature and precipitation, affecting the spatial distribution and productivity of future land use and land cover as result of differential changes in growing conditions. Other climate change effects, such as changes in the water resources needed to support future cropland expansion and intensification, are often neglected. In this study, we demonstrate how including different types of responses to climate change influences the simulation of future changes to land use and land cover, and land management. We study the influence of including different climate change effects in land system modeling step by step. The results show that land system models need to include numerous simultaneous climate change effects, particularly when looking at adaptation options such as implementing irrigation. Otherwise, there is a risk of biased impact estimates leading either to under- or overestimation of the consequences of land use change, including land degradation. Spatial land system models therefore need to be developed accounting for a multitude of climate change impacts, uncertainties related to climate data, and an assessment of the sensitivity of the outcomes toward the decisions of modellers on representing climate change impacts.

KEYWORDS
abandonment, climate change, cropland intensification, irrigation, spatial allocation, water resources

1 | INTRODUCTION

Climate change affects the way we use and manage the land considerably (Pielke et al., 2011; Rosa et al., 2014). To support the development and evaluation of effective land degradation and climate adaptation strategies, future changes to land use need to be explored (Pielke et al., 2011). Despite the advances in land use change models, it remains a significant challenge to simulate responses to climate change impacts in future land use scenarios (Rounsevell et al., 2014). However, considering the full range of potential climate change impacts when modeling future land use is of high importance for improving our understanding of Earth system processes.

Spatial land use models are necessary to identify future hotspots of land use change and have become a central part in integrated

assessment models (Letourneau et al., 2012; Schaldach et al., 2011). A majority of spatial land use models operating on different scales consider climate change as an environmental factor, influencing the spatial distribution of future land use, impacting land suitability or potential yields, as allocation factors (e.g., PLUM, Engström et al., 2016). Considering the changes to yields or cropland productivity influences the extent of cropland needed to satisfy future demand for food (Engström et al., 2016). Nevertheless, numerous climate change impacts are still neglected in land use models, most notably changes to productivity that feedback on the entire demand–supply balance (Alcamo et al., 2011).

The uncertainties arising from such inattention range from misplacement of cropland intensification and expansion, overestimation of irrigated cropland, and grazing intensification in areas otherwise too arid, to name a few (Malek & Verburg, 2017b). Misrepresenting the extent of future changes to land use limits the identification of the scale and nature of the consequences of future land use change. Future allocation of irrigated cropland will have an effect on finding locations with serious water scarcity (Scherer & Pfister, 2016) and studying the influence on water runoff and freshwater resources (Falkenmark et al., 2014). Underestimating future cropland intensification could suggest that investment in technological improvements needed to increase yields might actually be significantly higher (Mueller et al., 2012). Cropland intensification can also result in reduced water quality, land degradation, and biodiversity loss (Foley, 2005; Young et al., 2005). On-the-other-side, cropland extensification and abandonment can result in a wide range of positive consequences, such as decreased soil erosion and ecological restoration (Rey Benayas & Bullock, 2012). Particularly, in semi-arid regions, it can also have undesirable effects. Abandonment of cropland can lead to loss of landscape heterogeneity, increased occurrence of fires, biodiversity loss, and reduced water provision (Pueyo & Alados, 2007; Rey Benayas, 2007). In marginal arid areas, it can also lead to land degradation and desertification (García-Ruiz & Lana-Renault, 2011; Lesschen et al., 2008). Overall, changes to land use also have a profound effect on the release and uptake of carbon (Houghton & Nassikas, 2017; Pugh et al., 2015) and biodiversity (Pouzols et al., 2014).

In this study, we demonstrate how considering climate change impacts in land system models affects our understanding of climate change responses. We evaluated the influence of including different climate change impacts on the allocation of large-scale responses in land-use, while following global outlooks for future food production. Particularly, we focus on land use responses in a (semi)arid region characterized by high water stress, such as implementing irrigation, changes to cropland intensity, cropland diversification, or change of crop types. First, we consider spatially explicit future changes to precipitation and temperature. Secondly, we study the effect of changes to the spatial extent of rainfed cropland and livestock grazing. We then focus on changes to cropland productivity, by accounting for spatial variability of productivity. Subsequently, we study the effect of limiting and reducing freshwater resources. Finally, we demonstrate the uncertainties in land system models related to the spatial distribution affected by different climate change impacts.

2 | METHODS

2.1 | Demonstration area

As an example, we use the Mediterranean ecoregion, a region describing the approximate original extent of Mediterranean natural communities (Olson et al., 2001) in the Middle East, Northern Africa, and Southern Europe (Figure 1). It covers 2.3 million km^2 in 27 countries with around 420 million inhabitants (EUROSTAT, 2016a, 2016b). It is a densely populated area, severely affected by land degradation and constrained with water resources (Fader et al., 2016; Giorgi & Lionello, 2008). The region hosts diverse land systems of different intensities and levels of (multi) functionality (Malek & Verburg, 2017a). A large part of the region is covered by low-intensity cropland and traditional multifunctional mosaic systems, with centuries of low impact livestock, cropland, and forestry activities (Blondel, 2006). On the other side, intensive cropland systems produce most of the crops in the region, both for domestic consumption and exports. Intensive cropland is limited to areas with sufficient rainfall or needs to be irrigated and usually has high water demands (Daccache et al., 2014) and a bigger land degradation impact (Zalidis et al., 2002). Growing population and food demands, future climate change, and high water stress, make it a suitable area to demonstrate how considering responses to climate change affects simulating land management on a large (continental) scale.

2.2 | Land system modelling

2.2.1 | CLUMondo model introduction

We used CLUMondo, where future land system changes (changes in land-use and land cover, land management, and intensity) are driven by predefined demands for specific goods, for example crops or livestock, while considering local spatial characteristics (van Asselen & Verburg, 2013). These goods are provided by land systems based on their spatial characteristics (e.g., average cropland extent or intensity). Typically, detailed spatially explicit land use or land cover (LULC) models simulate changes from one distinct LULC to another and are based on dominant LULC in the units of simulation. CLUMondo, on-the-other- hand, can simulate changes in cropland, grazing, and settlement intensity. It can, therefore, capture the diversity of land use and land management and can also simulate climate adaptation options. This is particularly important for (semi)arid regions, as the model can represent the equipment of existing cropland with irrigation in areas otherwise too arid for rainfed cropland, instead of converting it to a different land cover type (cropland to noncropland). Additionally, the model can consider services provided by land systems. It can account for multifunctional land systems that would be considered as a single-functional land cover otherwise (e.g., silvopastoral mosaics providing both forest ecosystem services and grazing would either be considered as woodlands or grazing lands in a land cover based model). CLUMondo allocates future changes to land systems based on their allocation suitability, explained in the following sections (van

FIGURE 1 Location and spatial extent of the Mediterranean ecoregion (dark grey)

Asselen & Verburg, 2013). CLUMondo (and other models from the CLUE model family) is one of the most widely used spatial land use models, with applications on different scales all around the world. Examples range from local to regional-scale studies in China (Liu et al., 2017; Nie et al., 2020; Wang et al, 2019, 2020; Zhu et al., 2020), Slovakia (Pazúr & Bolliger, 2017), Northern Thailand (Arunyawat & Shrestha, 2018), the Lao PDR (Ornetsmüller et al., 2016), and the wider Mediterranean region (Malek et al., 2018), to global-scale simulating future land use change and land use intensification (van Asselen & Verburg, 2013; Wolff et al., 2018). Additionally, CLUMondo results have been used in numerous global-scale assessments of consequences of land use change (Bolochio et al., 2020; Egli et al., 2018; Pouzols et al., 2014; Schulze et al., 2020; Sorte et al., 2017). Finally, the model is similar to other spatial allocation models (where socioeconomic, soil, terrain, and climate characteristics define the spatial pattern of land use change), making it a suitable choice to demonstrate land use responses to climate change. We modified CLUMondo with modules that include land use changes representing climate change adaptation, explained in the later sections. The *Mediterranean Land Systems Map for 2010* served as a baseline (S1), with each land system classified as a combination of land cover (cropland, tree cover...), management (irrigation, intensity, crop type), and livestock grazing density at a 4 km² spatial resolution (Malek & Verburg, 2017a).

2.2.2 | Demand types and scenarios

We focused on four demand types, supplied by the land systems: annual and permanent crops, livestock, and urban areas. Future demands follow the SSP2 (Shared Socioeconomic Pathway) scenario projections for the region for the year 2050 (S2). Demands for annual and permanent crops and livestock are based on the SSP2 marker scenarios for food production (Fricko et al., 2017; Popp et al., 2016; Riahi et al., 2016). Under annual crops, we aggregated the production for the year 2010 for major cereals (barley, maize, rice, and wheat) and vegetables (fresh vegetables with potatoes and tomatoes). For permanent crops, we aggregated the 2010 production of fruit, olives, and dates. The production of both annual and permanent crops is based on reported agricultural production statistics (EUROSTAT, 2016b, 2010). For both crop types, we then used relative changes from the SSP2 marker scenario. The demand for urban areas followed the population change rates for the SSP2 scenario (Kc & Lutz, 2014). The land systems supply of these goods is described in the Supplementary Material (S3). Generally, intensive rainfed and irrigated cropland provide considerably more annual and permanent crops and livestock. Livestock supply, expressed in aggregated livestock units of bovines, goats, and sheep, was derived from a global livestock density map (Robinson et al., 2014).

2.2.3 | Allocation suitability and explanatory climate variables

To fulfill the demand for a specific good (e.g., annual crops), CLUMondo considers the locations with highest suitability for the systems that contribute to this demand. This means that the model considers local socioeconomic and biophysical contexts when allocating national or regional demands for crops, livestock products, living space, and other goods. Allocation suitability was calculated in a previous study (Malek et al., 2018) for each land system by studying the relationship between the spatial distribution of a land system and 19 explanatory variables (S4), including socio-economic (such as

population density, access to markets, and distance to roads) and biophysical (soil characteristics, terrain, and climate). These relationships were studied with logistic regression, used to derive suitability maps, which range from 0 (low suitability) to 1 (high suitability, see example in S5).

2.3 | Land use change responses to climate change

We studied land use responses that are most representative and anticipated climate change adaptation options for the Mediterranean (Table 1) and other (semi)arid areas with severe water restrictions and large shares of low intensity cropland and woodlands (Harmanny & Malek, 2019; Sowers et al., 2011). Climate change impacts the productivity of (rainfed) cropland, resulting in numerous adaptation responses (Smit & Skinner, 2002). First, adaptation in the region is mostly related to reducing water stress and allowing cropland activities in areas with insufficient rainfall. To address this, we studied the extent of future implemented irrigation. Secondly, we focused on changes to cropland intensity. It is likely that extensive rainfed cropland will intensify, but there are also areas, where intensive cropland could be extensified, for example, due to climate change and reduced water resources (Malek & Verburg, 2017b). Third, we focused on changes to crop types, particularly from permanent to annual crops (and vice versa). Changing to crop types with lower water demands has been identified as a potential adaptation response due to water shortages (Smit & Skinner, 2002). Finally, we studied the changes to functionality of land systems. We

focused on specialization and diversification of cropland activities, particularly significant for multifunctional land systems such as agroforestry systems (Sowers et al., 2011).

2.4 | Sequential study of climate change impacts

We performed six modelling experiments to study the effect of different representations of land use responses to climate change in the Mediterranean until 2050 step by step. This way, we studied the sequential impact of potential climate change responses, where we incrementally combine different ways of representing climate change impacts in the model. The modeling experiments are described in the next sections and follow the order as displayed in Figure 2.

2.4.1 | Experiment 1: No climate change considered

We first simulated future changes to land use without considering any climate change impacts. Climate variables (Table 1) remained stagnant in this experiment. Only changes to demands between 2010 and 2050 (annual and permanent crops, livestock, and urban areas) were influencing the allocation of future changes to land use and land management. This experiment served as our starting point and enabled a later identification of differences in allocation of land use change in case climate change is not considered at all.

TABLE 1 Land use responses as adaptation to climate change

| Land use response	Climate change adaptation	Land system conversions in the CLUMondo model
Infrastructure		
Implementing irrigation	Equipping cropland with irrigation to cope with increasing droughts	Rainfed land system to irrigated cropland
Changes to cropland intensity		
Cropland intensification	Increase in the intensity of cropland activities to increase crop production	Extensive cropland and multifunctional land systems to intensive rainfed cropland
Cropland extensification	Decrease in the intensity of cropland activities in areas less suitable for cropland	Intensive rainfed cropland to extensive cropland or noncropland land systems
Changes to crop type		
Annual to permanent	Replacing annual with permanent crops in areas more suitable for permanent crops	Annual to permanent cropland
Permanent to annual	Replacing permanent with annual crops in areas more suitable for annual crops	Permanent cropland to annual cropland
Specialization and diversification		
Cropland diversification	Diversify crop types by adding a new crop type in areas where intensification or irrigation are not possible (e.g., by adding permanent crops on formerly only annual crops)	Annual and permanent cropland systems to annual–permanent cropland system
Cropland specialization	Focusing on single-type cropland system to increase crop production	Annual–permanent cropland systems to annual or permanent cropland system
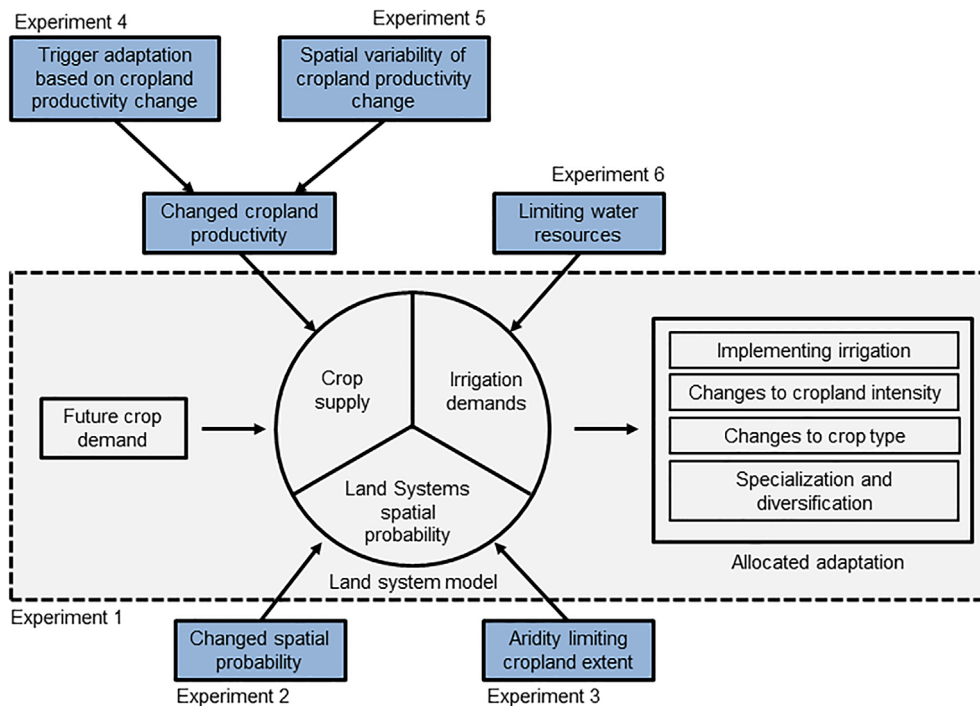
FIGURE 2 Flowchart of the sequential study. The gray square presents the first experiment without considering any climate change impacts. Every next experiment step (2–6) addresses additional climate change impacts described in the following sections [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Changes in the spatial extent to simulated land use response, compared to the previous experiment step in %

	Experiment (simulation sequence) comparison						
Land use response	**2 vs 1**	**3 vs 2**	**4 vs 3**	**5 vs 4**	**5 vs 3**	**6 vs 5**	**6 vs 1**
Implementing irrigation	+0.7	+13.8	+84.1	−33.5	+22.3	−22.8	+8.2
Cropland intensification	+6.3	+8.39	−6.5	+32	+23.5	+14.7	+63.2
Cropland extensification	+101.5	−41.73	+401.1	−86.6	−32.7	+35.7	+7.3
Annual to permanent	+121.2	−10.8	−0.4	−17.1	−17.5	−5.8	+53.3
Permanent to annual	+18.3	+1.4	+138.9	−46.8	+27.1	−34.2	+0.3
Cropland specialization	−2.6	+4	+122.1	−43	+26.6	−29.9	−10
Cropland diversification	−19.8	+2.7	+5.1	+2	+7.2	+61.4	+42.6

Note: 1) Initial basic run; 2) Changes to temperature, precipitation, and PET; 3) Limiting the spatial extent of specific land systems to areas with suitable climate; 4) Triggering response to climate change due to cropland productivity change; 5) Introducing spatial variability to cropland productivity; 6) Limiting water resources.

2.4.2 | Experiment 2: Climate change influencing the allocation suitability of land systems

The allocation suitability of each land system was changed annually by updating the climate explanatory variables: annual precipitation, mean temperature, and potential evapotranspiration (Table 2, S4). We used high-resolution 1 km CMIP5 climate model results for the three variables from Worldclim (Hijmans et al., 2005; Taylor et al., 2012) forced by the RCP4.5 greenhouse gas radiative forcing representative concentration pathway (RCP). The mean of gridded 19 CMIP5 simulation outputs (S6) was calculated for the year 2050 (represented by CMIP5 simulations for the period 2041–2060), and later, we applied a constant growth rate between the current climate and the 2050 projections for each pixel to generate annual maps. We resampled the climate data to match the 4 km^2 resolution of our

land system map by calculating the mean for each new aggregated cell. Climate variables were updated for each year of the simulation to generate annual variables, as CLUMondo operates in yearly time steps (Figure 2, step 2). This way we also prevented abrupt changes to location suitability, which could occur if we prepared decadal climate maps. We have chosen to use yearly mean data rather than seasonal data as for different crops in the regions the growing period is very different (winter wheat vs. summer season vs. permanent crops). We used future projections on annual mean temperature and annual mean daily temperature range from the same Worldclim dataset to calculate future annual potential evapotranspiration (PET) with the Hargreaves (Hargreaves & Allen, 2003) PET model (more details and equation available in S7). PET presents the ability of the atmosphere to remove water through evapotranspiration processes and affects the allocation suitability of rainfed

and irrigated cropland (Allen and FAO, 1998; Trabucco et al., 2008; Zomer et al., 2008).

2.4.3 | Experiment 3: Limiting the spatial extent of natural and semi-natural ecosystems and land management to areas with suitable climate

Changing the allocation suitability does not limit the occurrence of land systems on locations where the effects of climate change are beyond changes to temperature and precipitation. As in the suitability calculation, the factors are additive (and based on statistically derived relationships consisting of a multitude of location factors influencing the suitability), still a reasonably high suitability can potentially be attained under climatic conditions relatively unfavorable to agricultural use. This can, for example, be achieved in areas on suitable soil and gentle slopes that are close to major markets, despite less suitable climatic conditions. Given the large dataset with ample variation in all factors on which these empirical relations are estimated, it is unlikely that this situation occurs frequently. To limit the allocation of changes to natural and semi-natural ecosystems (such as forests and woodlands), intensive rainfed cropland and intensive livestock grazing under unfavourable climatic conditions, we implemented an exclusion factor (Figure 3) based on the aridity index (AI). The AI is an indicator used to quantify precipitation deficits over atmospheric water demand (UNEP, 1997; Zomer et al., 2008), and is calculated using precipitation and PET (S7). Areas with an AI below than 0.65 were defined as areas where forests cannot occur (Zomer et al., 2008). In these areas, forest expansion is not possible, and existing forests are converted to less denser woodlands. Such transitions have been observed in semi-arid regions, also in the Mediterranean, where increased drought and temperature have led to vegetation shifts or stand density reductions due to increased tree declines and mortality or altered fire regimes (Batllori et al., 2013; Cailleret et al., 2014; Camarero et al., 2011; Grant et al., 2013; Martínez-Vilalta & Lloret, 2016). We excluded intensive rainfed cropland in arid areas, where the AI is below 0.2 (Eitelberg et al., 2015; UNEP, 1997; Zomer et al., 2008). In these areas, we assigned that the model either needs to equip cropland with irrigation or abandon it (convert to noncropland land systems). Finally, livestock intensification (conversion to a system with a higher livestock density) was not possible in arid areas (AI below 0.2).

2.4.4 | Experiment 4: Triggering responses to climate change

Responses to climate change cannot be represented by only changing the allocation suitability or by defining areas with (un)suitable climate a-priori modelling. Projected changes to the productivity of rainfed cropland are also characterized by a high spatial variability (Figure 4).
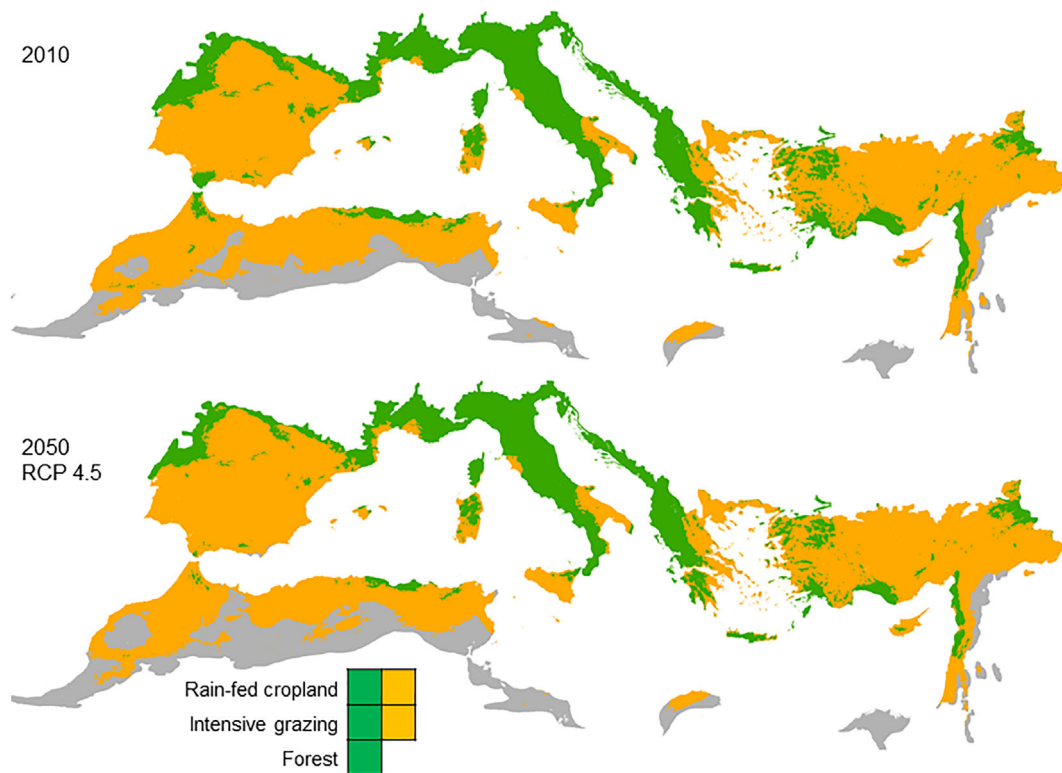

FIGURE 3 Limited spatial extent of forest, rainfed and intensive grazing systems, based on the aridity index (Zomer et al., 2008) (S6). The areas colored with yellow and green defined the spatial extent where rainfed cropland and intensive grazing are allowed and green areas where there are sufficient humidity to support forests [Colour figure can be viewed at wileyonlinelibrary.com]
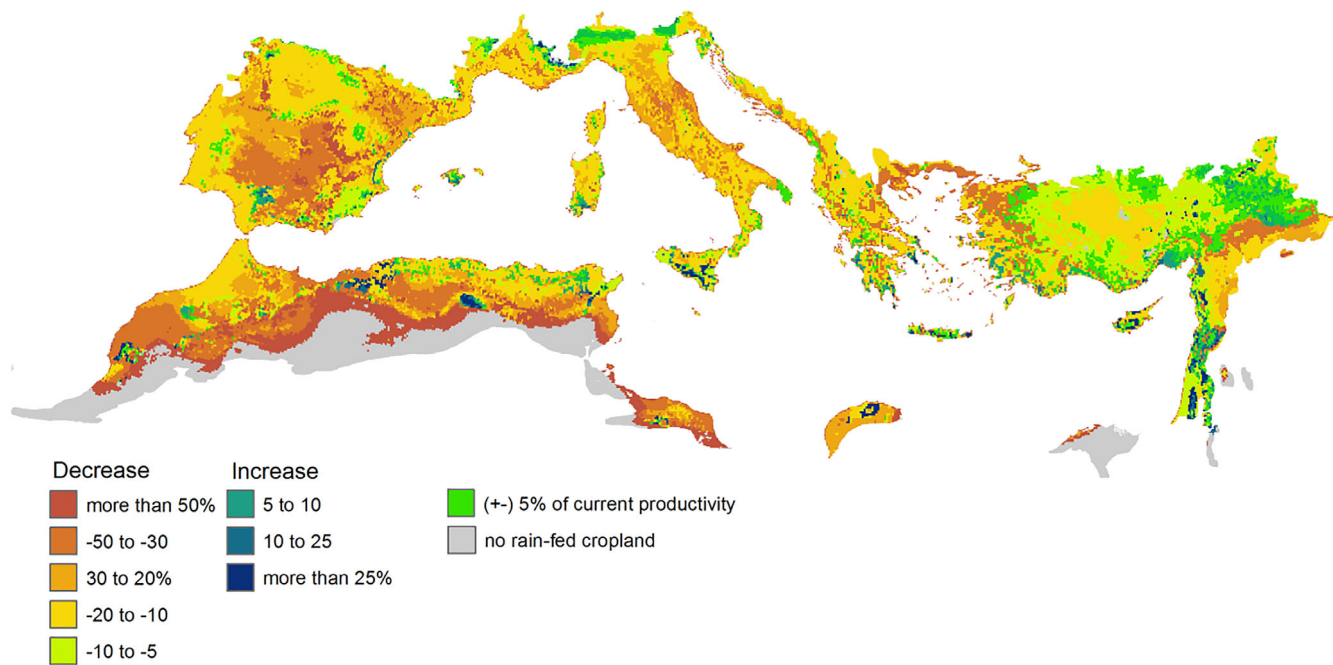
FIGURE 4 Changes to overall cropland productivity of land systems, based on Global Agro-Ecological Zones (GAEZ) (Fischer et al., 2008). The average land system output (e.g., annual crops) is corrected for each location with the future change of cropland productivity [Colour figure can be viewed at wileyonlinelibrary.com]

We present two approaches how to consider spatially varied changes to cropland productivity. In this experiment step, we identified areas where productivity decreases to such an extent that the current level of cropland output cannot be maintained and triggered land use change in these areas. This way, we were able to study which land use responses were simulated as most suitable to replace currently intensive rainfed cropland in areas with expected considerable decreases to cropland productivity. We used data on future changes to rainfed cropland productivity from the Global Agro-Ecological Zones—GAEZ, version 3.0, available on a 10 km resolution (Fischer et al., 2008). Although the GAEZ data were not simulated using the RCP scenarios, the B1 scenario is (to a large degree) similar to the applied RCP4.5 climate scenario, in terms of trends and the storyline (van Vuuren & Carter, 2014). Data on cropland productivity change on a similar spatial and temporal scale are scarce, and using a similar approach to the way we prepared future climate change data was not possible. Moreover, we aimed at considering overall productivity of rainfed cropland and did not want to focus on a single crop, which is why we used GAEZ. We focused on changes to the productivity of rainfed cropland until 2050, with a CO_2 fertilization effect.

Changes to land systems were triggered by defining conversion rules in CLUMondo. First, we looked at the differences in production (output) between land system types of different intensities (S3). This way, we could identify when a land system has to be changed to a system of a different intensity (lower or higher), if it is subject to changes in cropland productivity (either a decrease or an increase). These thresholds were used to trigger land system conversions, from a system with a higher cropland intensity to one with a lower. For

example, if a certain location was subject to a 50% decrease in cropland productivity due to future climate change, it had to change to a cropland system with a lower intensity, to an irrigated system, or to a noncropland system. In the Mediterranean region, these thresholds vary slightly among different subregions, however, generally correspond to values presented in Figure 5. We based the thresholds on the assumption, that rainfed cropland is only possible in areas, where the climate allows such productivity. Otherwise, the rainfed cropland subject to productivity decrease either has to change to a system of lower productivity, be equipped with irrigation, or has to be abandoned (Figure 4).

2.4.5 | Experiment 5: Effect of spatial variability of cropland productivity

A second approach on considering the spatial variability of cropland productivity does not involve triggering land-use changes, but allowing for more subtle changes to cropland productivity. In this step, we accounted for changes to productivity in every location on a single cell resolution, leaving the model to calculate and allocate the amount of necessary land use responses. This experiment does not follow the previous step where changes were triggered but builds upon experiment 3 (shown in Figure 2). The output of rainfed cropland land systems was updated each year of the simulation, using the change in production compared to the initial state (2010). In practice, we implemented this by multiplying the spatially explicit output of rainfed cropland (S3) using GAEZ productivity change data (Figure 4). Every
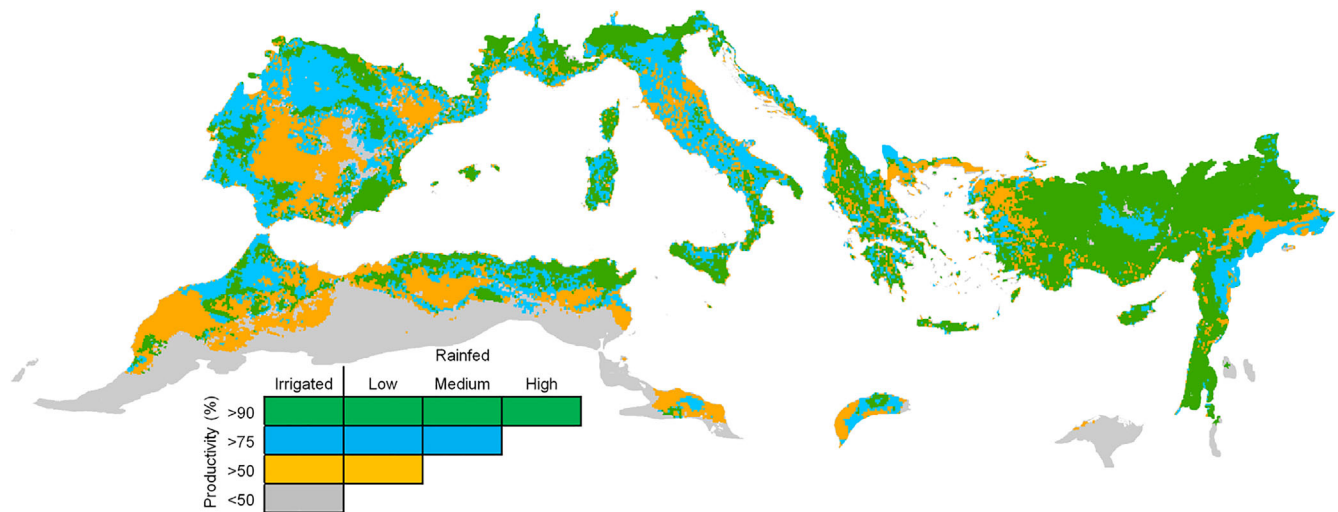
FIGURE 5 Allowed extent of rainfed cropland systems following projected changes to cropland productivity, based on Global Agro-Ecological Zones (GAEZ) (Fischer et al., 2008). Changes to rainfed cropland systems are triggered in areas where productivity changes to a degree that does not allow a rainfed system of a particular intensity [Colour figure can be viewed at wileyonlinelibrary.com]

location has a different output in terms of crop production, whereby it deviates from the average land system output for the region (S3). For example, where a certain location is subject to a 50% decrease in cropland productivity due to future climate change (using the same example as in experiment step 4), the model here evaluates by itself whether the area will be converted to a system with a lower intensity, an irrigated system or a noncropland system, based on local suitability and competition with other land systems and areas. However, if a location experiencing a decline in cropland productivity is not converted, the model needs to allocate more cropland elsewhere, to account for a lower contribution of this location to the total crop production. This approach is less strict than experiment 4, as it allows for subtle decreases in cropland productivity (without a-priori defining thresholds). At the same time, this experiment step also allows for increases in cropland productivity due to future climate change, although areas experiencing increases under the RCP4.5 scenario in the Mediterranean region are rare (Figure 4).

2.4.6 | Experiment 6: Limiting water resources

Future climate and socioeconomic change is expected to result in an expansion of irrigated cropland (UNESCO, 2006). Declines in freshwater resources available for irrigation are however also expected and considered among the most significant climate change impacts in semiarid areas and particularly in the Mediterranean (Brown et al., 2017; Iglesias & Garrote, 2015). Limiting water resources has proven to have a significant effect on both the simulated extent of irrigated areas, as well as intensive rainfed cropland (Malek et al., 2018).

CLUMondo can limit the allocation of land system change based on available freshwater resources. This is implemented by applying a threshold on the total regional irrigation water consumption, which cannot be exceeded. We did this for several reasons. Water resources

in the Mediterranean (particularly in Northern Africa and the Middle East) are already used unsustainably and increases in water withdrawals are not possible in most parts of the region. For example, in the Middle East, over 90% of available water resources are already extracted and, in NW Africa, over 30% (FAO, 2016; Malek et al., 2018). Additionally, a considerable share of water basins in the Mediterranean is depleted (Brauman et al., 2016). Irrigated systems have, in the demonstration area, the highest crop output per unit (S3). They also have irrigation water needs, which limits their expansion. In case of a reached limit of water available for irrigation, CLUMondo therefore has to consider nonirrigated land systems, when trying to satisfy additional demands for crops. The extent of irrigated cropland was based on the map of areas equipped with irrigation (Siebert et al., 2005; Siebert et al., 2013), which we associated with reported irrigation water consumption values for each country from reported national and subnational statistics. For the countries in the European Union, we used values collected by EUROSTAT for either the whole countries or only subnational regions that are in the Mediterranean ecoregion (EUROSTAT, 2010). For other Mediterranean countries, we used values reported by the countries to the FAO (FAO, 2016), and for Egypt, we corrected the national irrigation water consumption to exclude the areas outside the Mediterranean ecoregion (Mohamed, 2016). Irrigated land systems were characterized by a mean value of irrigation water consumption per unit of land system (S3). The amount of total available water resources for irrigation was also derived from reported statistics (EUROSTAT, 2010; FAO, 2016; Mohamed, 2016). We reduced the amount of available water resources until 2050 using changes to total regional precipitation as a proxy (S8, Hijmans et al., 2005). Although this is a simplification, future projections on available water resources (only considering changes to precipitation) for this region at this spatial and temporal scale were not available. Finally, to more realistically simulate how farmers in the regions will adapt to limiting and decreasing water

resources, we applied a moderate irrigation efficiency improvement, based on (Malek & Verburg, 2017b)—otherwise increases in irrigated areas would not have been possible. Reported irrigation efficiency in the region ranges from 53.7% in Western Balkans and Turkey to 66.2% in NW Africa (FAO, 2016; Malek & Verburg, 2017b), and we increased the efficiency to 71.3%, considering incremental improvements to irrigation technology and type of irrigation systems.

2.5 | Comparing simulations

We looked at the differences in the spatial distribution (locations) and spatial patterns between the simulations using a geographic information system (GIS). First, all experiment simulations were compared on a cell-by-cell basis, in terms of locations of projected land use change responses to climate change. Secondly, we compared the spatial extent of studied land system processes of different steps of our experiment. Then, the agreement between the simulation outcomes was compared by calculating the Kappa simulation ($K_{simulation}$) index. Kappa simulation describes the agreement between allocated land system change, while accounting for persistence (van Vliet

et al., 2011). This is necessary, as focusing on overall agreement between simulation results (overall maps) overestimates the agreement between different maps (van Vliet et al., 2011). Areas that do not change (for example regions covered by desert areas) would contribute to higher agreement between the maps. The $K_{simulation}$ is a product of $K_{transloc}$, describing the agreement in allocation, and $K_{transition}$, describing the agreement in quantity of land system change (van Vliet et al., 2011). Finally, we looked at the agreement of allocated land use change responses and the extent of additional and omitted allocation of subsequent steps of our analysis. This way, we could identify potential over- and underestimation of land use responses in case climate change is not fully considered.

3 | RESULTS

3.1 | Comparing the spatial distribution of responses in land use change

First, we present the spatial distributions of land use responses for each step (Figures 6 and 7). The spatial distribution of responses in
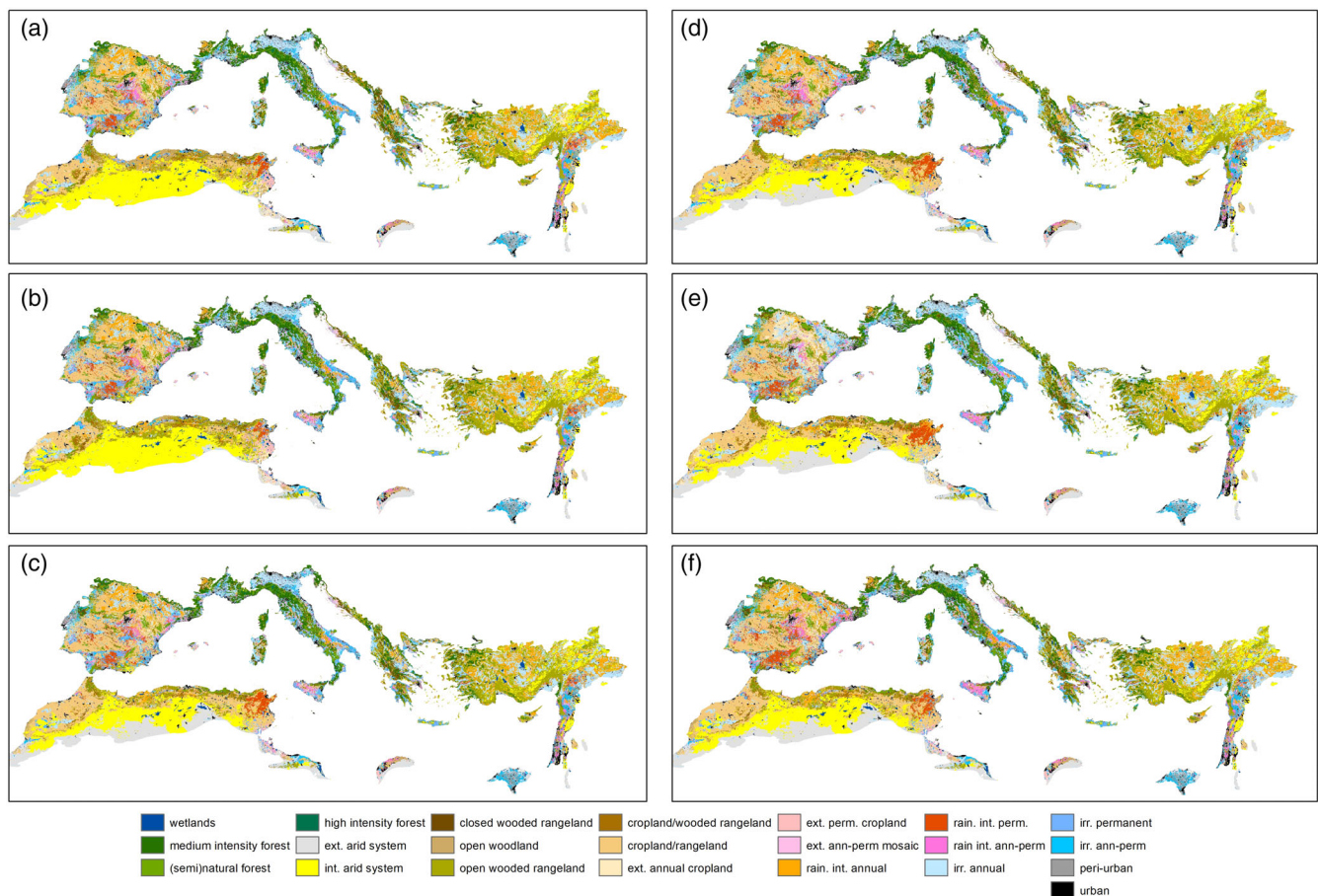

FIGURE 6 Simulated future land use for the year 2050 under different experiments: (a) Exp.1: basic simulation, (b) Exp.2: Changes to temperature, precipitation, and potential evapotranspiration (PET), (c) Exp.3: limiting the spatial extent of specific land systems to areas with suitable climate, (d) exp.4: Triggering response to climate change due to cropland productivity change, (e) exp.5: Introducing spatial variability to cropland productivity, and (f) Exp 6: limiting water resources [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Allocated irrigation, cropland intensification, and extensification in different experiments: (a) Exp.1: Basic simulation, (b) Exp.2: changes to temperature, precipitation, and potential evapotranspiration (PET), (c) Exp.3: limiting the spatial extent of specific land systems to areas with suitable climate, (d) Exp.4: triggering response to climate change due to cropland productivity change, (e) Exp.5: introducing spatial variability to cropland productivity, and (f) Exp 6: limiting water resources [Colour figure can be viewed at wileyonlinelibrary.com]
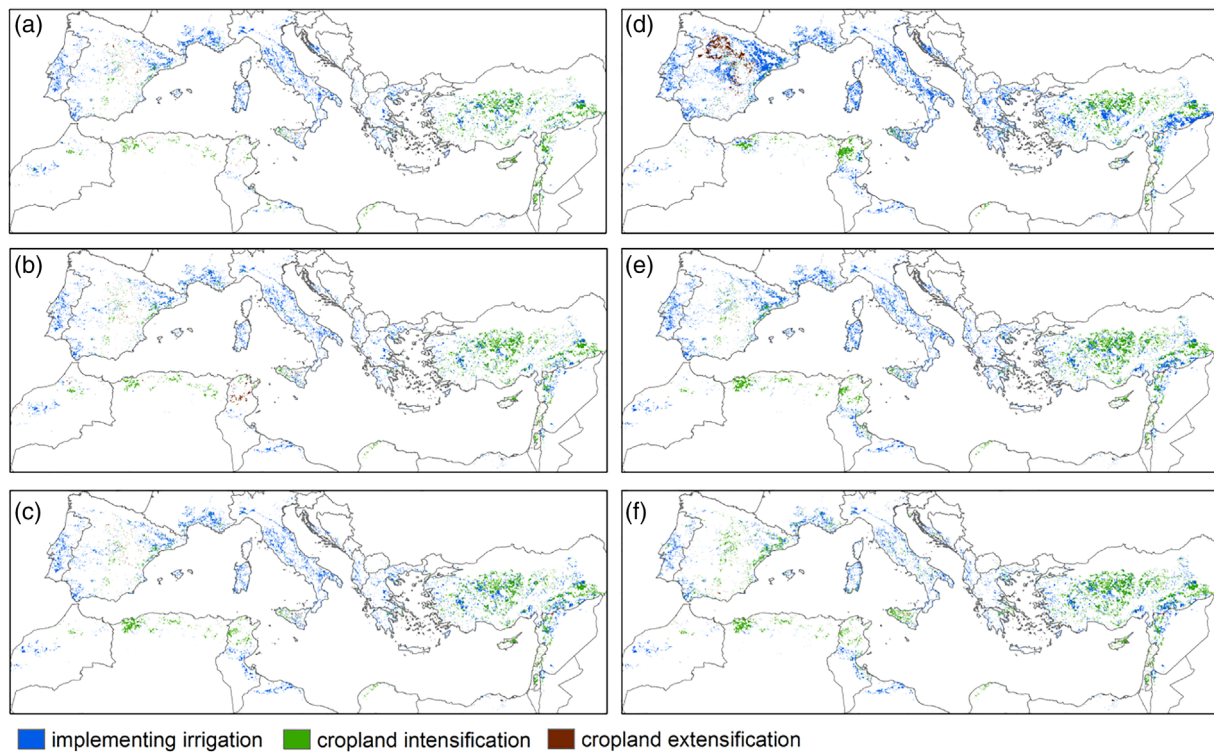
land use change varies substantially when considering different climate change impacts. This is valid both in terms of the locations of projected land use change, as well as in the spatial extent. The land use responses occurring on a large spatial extent in all simulations are irrigation implementation, cropland intensification, and extensification. Considering few or no climate change impacts generally underestimates the spatial extent of intensification, particularly in areas where rainfed cropland will still be possible (based on the assumptions in our model and climate characteristics). This can be observed most notably in central Turkey and NW Algeria. The model allocated new irrigation on a large scale when introducing additional climate change impacts without limiting water resources (Figure 7d,e). The final experiment with reduced water resources resulted in the smallest extent of new irrigated cropland.

Most notable deviations can be observed in the extent of cropland extensification in the second (changes to climate) and fourth experiment (triggered response to climate change). The changed allocation suitability for rainfed cropland due to changes to temperature, precipitation, and PET lead to significant extensification in Tunisia (Figure 6b). More cropland in that region remained persistent when limiting the spatial extent of rainfed cropland due to aridity. This demonstrates the sensitivity of the model to slight changes to the allocation suitability and the necessity of controlling the model with expert-based rules (such as limiting the allocation of rainfed areas in arid areas). The largest extent of extensified rainfed cropland was

simulated in step 4, where we triggered land use responses. Almost all rainfed croplands in northern Spain were extensified in this simulation, with significant new irrigated areas east of this region (Figure 7d). This area was not subject to extensification in none of the other simulations, suggesting that triggering changes to land systems are too influential.

Changes to crop types or the extent of cropland diversification or specialization is projected on a much smaller spatial extent (S9) and is limited to specific areas. For example, large-scale changes were mostly simulated in Tunisia and South Italy (Figure 8). Also here, there are considerable changes between different simulations when looking at these land use responses. Generally, all simulations allocated more changes from permanent to annual crops in the northern Mediterranean and more changes from annual to permanent in the southern Mediterranean. Substituting annual with permanent crops is projected to occur on a large scale when the allocation suitability is updated with climate change. This process is therefore particularly sensitive toward such changes. Large-scale substitution of permanent crops with annual crops occurs when triggering changes to rainfed cropland. In this simulation, vast areas of currently intensive rainfed cropland were triggered to change, mostly resulting in extensification. Simultaneously, permanent cropland was converted to cropland with annual crops in some areas, such as northern Tunisia and NW Italy. Interestingly, limiting water resources resulted in the largest extent of cropland diversification and the smallest extent of specialization (Figure 8,
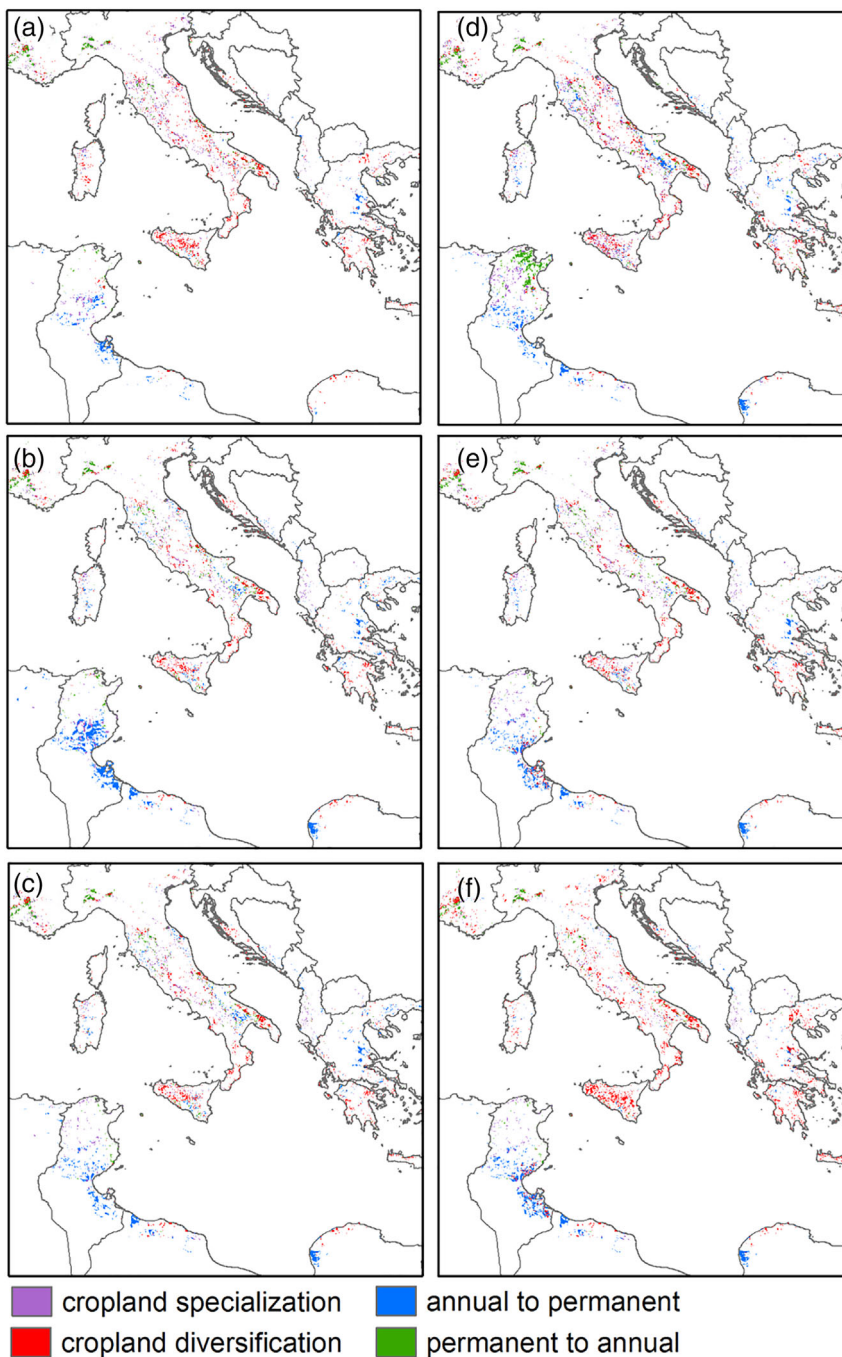
FIGURE 8 Allocated cropland specialization and diversification and changes to crop types in different runs focusing on Italy, Greece, Libya, and Tunisia: (a) Exp.1: basic simulation, (b) Exp.2: changes to temperature, precipitation, and potential evapotranspiration (PET), (c) Exp.3: limiting the spatial extent of specific land systems to areas with suitable climate, (d) Exp.4: triggering response to climate change due to cropland productivity change, (e) Exp.5: introducing spatial variability to cropland productivity, and (f) Exp.6: limiting water resources [Colour figure can be viewed at wileyonlinelibrary.com]

■ cropland specialization ■ annual to permanent
■ cropland diversification ■ permanent to annual

Table 2). Diversification of cropland activities, in this region, tends to be underestimated when considering fewer climate change impacts. The model recognized it as the most viable strategy to satisfy the demand for both annual and permanent crops.

3.2 | Comparing the extent of allocated land use change responses to climate change

Introducing additional means to represent climate change impacts significantly affects the allocation of land use change responses (Table 2, S9). Already updating the allocation suitability maps with changed temperature, precipitation, and PET (experiment 2) leads to substantial changes to land system conversion. Most notable examples are cropland extensification and changes from annual to permanent cropland, which more than doubled compared to the simulation without any climate change impacts (Table 2).

Limiting the expansion of rainfed cropland systems and woodlands in arid areas (step 3) considerably reduces the extent of cropland extensification. Conversions from annual to permanent crops continue being allocated on a large spatial extent. Except for implementing irrigation, all other processes are allocated to a similar degree.

The results suggest that spatially explicit land system modeling is very sensitive to predefined locations where conversions need to

occur (experiment step 4). Triggering changes to rainfed cropland in areas experiencing a decline in productivity results in more irrigation, with changes from permanent to annual crops and cropland specialization allocated to twice as many areas, compared to the previous simulation. Cropland extensification deviates most compared to any other simulation, occurring on four times as many areas (Table 2). On annual cropland where land system conversions were triggered, the model mostly chose to extensify or abandon and not to implement irrigation. Rainfed intensive permanent cropland was mostly converted to annual crops. Both resulted in additional irrigation elsewhere, mostly on extensive rainfed cropland.

Introducing spatial variability to cropland productivity (experiment 5) results in more implemented irrigation, cropland intensification, and specialization and changes from permanent to annual crops, when compared to a similar simulation without spatially explicit cropland productivity (step 3). Compared to step 4 (triggered land system change), this step allocated more intensification and allocated considerably fewer other adaptation options. Overall, this step allocated the smallest extent of cropland extensification (Table 2, S9).

The difference between the final two simulations (5 and 6) suggests a 30% overestimation of irrigation implementation, in case water withdrawal is not restricted and reduced. The final simulation has the largest extent of cropland intensification and diversification compared to other model runs. This is mostly on the account of limited water resources; more food demand needed to be satisfied through intensification on rainfed cropland. Interestingly, this simulation allocates most cropland diversification (Table 2, S9). Comparing this final run with the initial simulation demonstrates which processes are most impacted by the inclusion of climate change impacts (Table 2). Most significant differences can be observed for cropland intensification and diversification and changes from annual to permanent crops.

3.3 | Comparing the spatial (dis)agreement

3.3.1 | Spatial (dis)agreement of experiment simulations

When looking at the spatial agreement between the final simulation results, we can observe how implementing additional climate change impacts spatial distributions of future land use and land management (Table 3). Maps with fewer climate change impacts are more similar to each other, and the same is valid for maps with more implemented climate change impacts. Comparing the initial basic simulation (step 1) with other simulations shows that the spatial disagreement ranges between 24% and 51%. Already by updating climate change variables (step 2), we see considerable differences. When triggering changes due to changed cropland productivity (step 4), we observe most spatial disagreement. The final two simulations where water resources are limited or not differ by 13%. Generally, future simulations are more similar in terms of spatial allocation ($K_{transloc}$) than type and size of change (K_{trans}, Table 3).

TABLE 3 Spatial agreement of final simulation results per experiment step

$K_{simulation}$	step2	step3	step4	step5	step6
step1	0.76	0.58	0.49	0.55	0.54
step2		0.69	0.55	0.63	0.60
step3			0.73	0.88	0.82
step4				0.73	0.68
step5					0.87
$K_{transloc}$	step2	step3	step4	step5	step6
step1	0.89	0.83	0.76	0.79	0.77
step2		0.94	0.84	0.88	0.86
step3			0.88	0.96	0.93
step4				0.88	0.87
step5					0.96
K_{trans}	step2	step3	step4	step5	step6
step1	0.85	0.71	0.65	0.70	0.69
step2		0.74	0.65	0.71	0.71
step3			0.83	0.92	0.88
step4				0.84	0.78
step5					0.91

Note: Shaded cells present values for two subsequent steps.

3.3.2 | Spatial (dis)agreement of individual land use change responses

The influence of different climate change impacts becomes more obvious, if we study specific responses in land use change (Table 4). Comparing the final (step 6) and initial simulation experiment (step 1), we can see that potential disagreement in allocating land use responses ranges from 47% to 86%. Generally, considering more climate change impacts leads to more additional allocation of all responses, except changes from permanent to annual crops and cropland specialization (Table 4). Comparing the simulation where water is limited with others is particularly important. Besides the demonstrated overestimation of new irrigated areas in case water resources are not limited, new irrigation is also characterized by potential misallocation (Table 4). For example, differences in the allocation of new irrigated areas are up to 52% when climate change impacts are not considered. Even the final two simulation experiments agree only in 71% of the locations, with most of the disagreement being on the account of potentially overestimating new irrigated areas (Tables 2 and 4).

More cropland intensification is allocated with adding climate change impacts. Contrary to irrigation, intensification tends to be underestimated in runs where fewer climate change impacts are considered. This is also valid when triggering response to reduced crop productivity resulted in simultaneous large-scale extensification of rainfed cropland and expansion of irrigated areas (Table 2). The underestimation of intensification is mostly on the account of overestimated irrigated cropland. Cropland extensification has the lowest spatial agreement between the simulations, with the disagreement ranging between 47% and 92% (Table 2). Even the last two simulations (5 and 6) disagree in almost half

TABLE 4 The influence of climate change impacts on the spatial allocation of different land use responses in %

		Experiment (simulation sequence) comparison						
		2 vs 1	**3 vs 2**	**4 vs 3**	**5 vs 4**	**5 vs 3**	**6 vs 5**	**6 vs 1**
Irrigation	Agreement in location	65.4	81.4	46	52.7	71.2	71	47.7
	Additional change	17.6	15.2	48.6	8.2	23	3.5	29
	Omitted change	17	3.5	5.4	39	5.8	25.5	23.2
Intensification	Agreement in location	72.1	79.1	55	55	75.7	79.9	50
	Additional change	16.6	14.1	19.9	33.2	21.4	16.2	43
	Omitted change	11.3	6.9	25.1	11.8	2.9	3.9	7
Extensification	Agreement in location	26.5	52.5	10.8	7.7	47.6	52.3	14.5
	Additional change	58.1	3.7	81.6	5	11.8	35.4	44.8
	Omitted change	15.5	43.9	7.6	87.2	40.6	12.3	40.7
Annual to permanent	Agreement in location	40.5	49.1	52	44.7	58.2	60	24.9
	Additional change	56.3	21.2	23.8	20.9	13.3	17.6	50.7
	Omitted change	3.2	29.7	24.1	34.4	28.5	22.4	24.4
Permanent to annual	Agreement in location	56.6	86.4	36.1	44.8	64.4	58.4	52.7
	Additional change	28.2	7.5	59.8	5.5	27.6	4.5	23.7
	Omitted change	15.1	6.1	4.1	49.7	8	37.2	23.5
Cropland specialization	Agreement in location	53.1	69.4	36.4	46.5	69.6	62.6	34.5
	Additional change	22.5	17	57.6	6.7	25.2	4.4	29.3
	Omitted change	24.4	13.6	5.9	46.8	5.2	33	36.3
Cropland diversification	Agreement in location	54.6	93.5	58.8	56.6	69.9	54.2	39.2
	Additional change	14.2	4.5	22.6	22.5	18	41	42.6
	Omitted change	31.2	2	18.6	20.9	12.1	4.8	18.2

Note: 1) Initial basic run; 2) Changes to temperature, precipitation and PET; 3) Limiting the spatial extent of specific land systems to areas with suitable climate; 4) Triggering response to climate change due to cropland productivity change; 5) Introducing spatial variability to cropland productivity; 6) Limiting water resources. Agreement values relate to all cells of the allocated process in both compared experiments.

of allocated future extensification. Contrary to other processes, extensification also does not show clear trends in terms of additional or omitted allocation. Comparing the initial (step 1) and final (step 6) simulation demonstrates that despite the relatively similar spatial extent of cropland extensification (Table 2), the actual allocation differs considerably. Already by comparing the first two simulations, we can see that locations of some allocated processes disagree in half of even more cases. This is valid for the allocated changes from annual to permanent crops (and vice-versa), and cropland specialization and diversification. By including more climate change impacts, the simulations tend to agree more in terms of location (steps 3, 5, and 6). Nevertheless, the final two experiments suggest that too many changes to crop types and cropland specialization were allocated. At the same time, additional cropland diversification was allocated.

4 | DISCUSSION AND CONCLUSIONS

4.1 | Representation of climate impacts in land use models

In this study, we demonstrated the influence of different ways to represent impacts of climate change on land use using a spatial land use model. The study did not aim to fully capture the reality of climate–land use interactions but rather evaluated the influence of different ways of model implementations of land use responses to climate change. Each subsequent experiment demonstrates the sensitivity of the land use model to implementing additional climate change effects. The results indicate that considerable differences in land use change result from not representing the different ways in which climate change impacts on land use change, as well as the impact of uncertainties in climate change data. The sensitivity of model output to the level of simplification of the relation between climate and land use leads to omission of important processes in modeling land use. Implementing climate–land use interactions is not straightforward, and in our model experiments, we still use only one directional approach (climate to land use). Nevertheless, we have shown that already a simple addition of climate change processes results in large differences in allocated land use patterns. For example, only updating the allocation suitability by changing climate variables leads to substantial changes in the allocation process. This can be attributed to different reasons. Reconfiguring the initial land systems map based on allocation suitability has been shown to impact the spatial distributions of land systems (van Asselen & Verburg, 2013). Moreover, the initial suitability map is subject to major uncertainties due to the input data used for preparing the land systems map (Fritz et al., 2011;

Malek & Verburg, 2017a; Popp, Rose, et al., 2014; Smith et al., 2010). Significant changes in land suitability for agriculture are, however, expected in the demonstration area due to increasing aridity (Gao & Giorgi, 2008).

The land change process most sensitive to changes in the allocation suitability was cropland extensification (Figure 9). In Tunisia (Figure 9a), vast areas of intensive rainfed permanent crops were simulated to extensify, despite only minor decreases in the allocation suitability (maximum decrease of 5%). Extensification was not allocated when excluding arid areas for all extensive cropland, forests, woodlands, and grazing areas (simulation step 3). The model is particularly sensitive to land system changes triggered by predefined decisions, mostly resulting in conversion to cropland systems of lower intensity due to changes in cropland productivity. Although reducing cropland intensity is possible, its allocated extent is unrealistic. In areas like northern Spain (Figure 9b), the model simulated wide-scale abandonment of currently intensive cropland. Large portions of these areas were subject to 5% to 25% decrease in cropland productivity (Figure 9b), which would still enable medium intensity cropland. Also here, the model was influenced heavily by the allocation suitability—irrigated cropland was allocated in other parts of the region, where the suitability was higher. In reality, farmers would avoid such large-scale abandonment of intensive cropland and equip the areas with irrigation, improve the cultivars, or switch to crops with lower water demands (Iglesias et al., 2010; Smit & Skinner, 2002).

4.2 | Plausibility of our results

Our study was experimental in nature, and therefore, the results should be interpreted with care. Nevertheless, some processes simulated in this study have been observed or simulated and confirmed in other studies. We simulated considerable increase in irrigated areas due to climatic limitations and comparably higher output of irrigated cropland systems. Equipping existing cropland with irrigation has been identified as the main strategy to increase cropland production across the region and to adapt to future climate change (Iglesias & Garrote, 2015; Mueller et al., 2012). We identify that not limiting water resources potentially leads to overestimation of the extent of irrigated cropland and underestimation of cropland intensification. This is based on the assumption made that irrigation withdrawal in the area cannot increase. This assumption is reasonable for our study area, where water resources
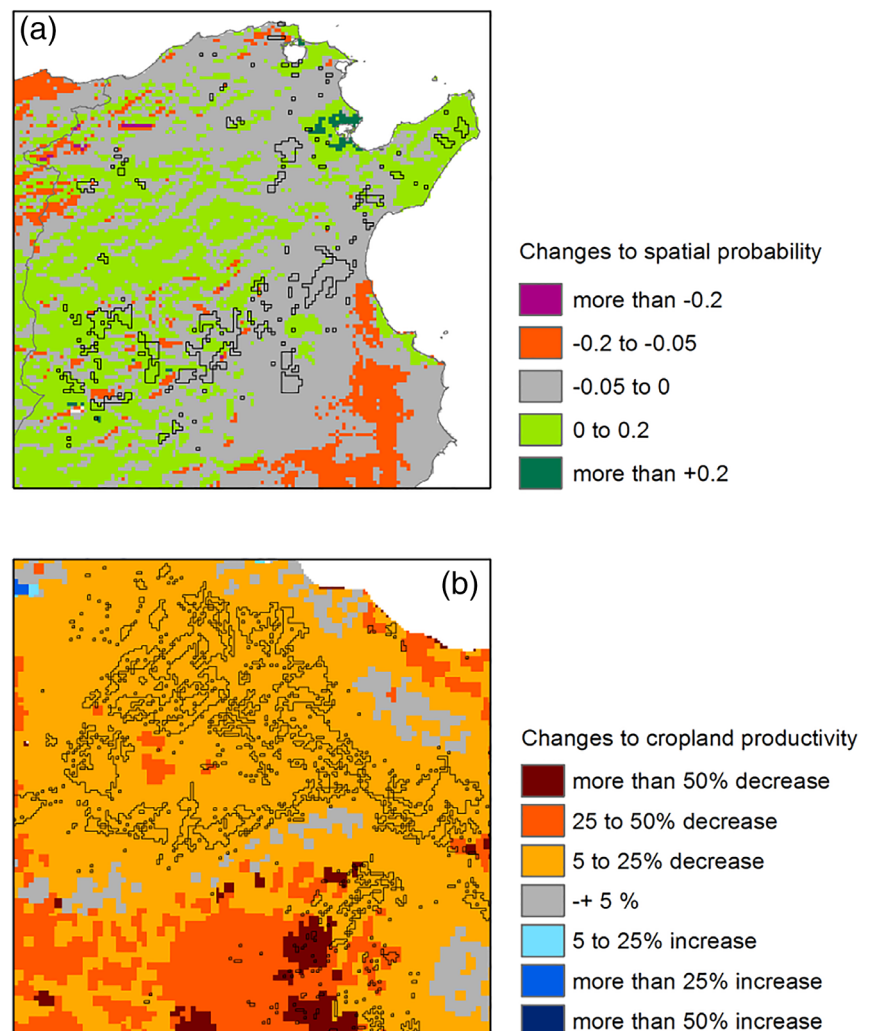

FIGURE 9 Two examples of misrepresenting land system change (marked with black) due to inadequate consideration of climate change impacts: (a) extensification of intensive rainfed permanent cropland in Tunisia due to decreased allocation suitability, when changing climate variables only (experiment 2) and (b) extensification of rainfed annual cropland in Spain when land system change is triggered due to changes to cropland productivity (experiment 4) [Colour figure can be viewed at wileyonlinelibrary.com]

might decrease even more drastically than assumed in the model experiment (Arnell, 1999; Iglesias et al., 2007). Improving the irrigation efficiency even more than the levels we applied could enable additional irrigated areas and will be necessary due to future climate change (Fader et al., 2016). Such efficiency improvements would mostly result in a decrease in water lost or used inefficiently and in lower costs related to irrigation water recycling and desalination (Chaturvedi et al., 2015). In order to test future adaptation to support agricultural and water policies in the region, changes to irrigation water requirements therefore need to be considered. On the other side, agricultural efficiency has been identified as the most influential determinants in land use models and could therefore lead to more uncertainty in our results (Stehfest et al., 2019).

At the same time, our results suggest substantial increases in cropland intensity in the Mediterranean. Similar scales of cropland expansion or intensification have been observed in the majority of other large-scale modeling approaches for the region (Prestele et al., 2016). This might seem counterintuitive, given the semi-arid context and expected future climate change trends in the Mediterranean. However, large parts of the region's rainfed cropland are characterized by large yield gaps, which can be decreased with improved nutrient management (Mueller et al., 2012), increased access to fertilization inputs (Pala et al., 2011), and alterations in tillage methods (Devkota & Yigezu, 2020).

4.3 | Uncertainties and limitations

Spatially explicit models, where land/allocation suitability is a central part of the allocation algorithm, such as CLUMondo (or CLUE) model, are widely used to simulate future land use changes and their consequences. CLUMondo in particular has been used in numerous large-scale studies that considered climate change impacts on land-use (Table 5). While climate variables influenced the land/allocation suitability in all provided examples, they were mostly static using baseline data. Climate change impacts considered in such models mostly affect land suitability, with other climate change impacts being neglected.

There are a number of uncertainties related to limiting water resources. While this study presents an advancement compared to other spatial allocation models that do not consider that water resources are finite, we still considered water resources on an aggregate national level, as reported by statistics. In reality, water resources are unequally distributed (Gerten et al., 2011), meaning that the expansion of irrigated areas would in reality be limited to areas with sufficient water available for irrigation. Additionally, particularly in densely populated areas such as the Mediterranean, water use for irrigation would compete with other users, for example, urban areas (Flörke et al., 2018). Moreover, in several parts of the region, water resources are already depleted (Brauman et al., 2016), impacting

TABLE 5 A selection of large scale studies using the CLUMondo/CLUE spatial allocation model and how climate change was considered in the study

Study	Area / scale	Objective	Climate change representation
(Verburg & Overmars, 2009)	Europe/continental	Land use change	Climate variables affecting land suitability—static (annual temperature, annual precipitation, potential evapotranspiration during the growing season, water deficit)
(Verburg et al., 2006)	Europe/continental	Land use change	Climate variables affecting land suitability—static (annual temperature, annual precipitation, summer precipitation, precipitation in growing season, count of cold months <0°C, count of warm months >15°C)
(van Asselen & Verburg, 2013)	Global	Land use change and intensification	Climate variables affecting land suitability—static (annual temperature, annual precipitation)
(Xia et al., 2016)	Northeast China/regional	Land cover change	Climate variables affecting land suitability—static (annual temperature, annual accumulated temperature ≥0°C, annual accumulated temperature ≥10°C, annual precipitation)
(Liu et al., 2017)	Northern China/regional	Intensification, grassland conversion	Climate variables affecting land suitability—static (annual temperature, annual precipitation, climate zone)
(Eitelberg et al., 2016)	Global	Livestock grazing, demand for biodiversity, and carbon sequestration	Climate variables affecting land suitability—static (annual temperature, temperature of coldest month, precipitation)
(Malek et al., 2018; Malek & Verburg, 2017b)	Mediterranean/continental	Intensification, multifunctionality, irrigation	Climate variables affecting land suitability—dynamic (annual temperature, annual precipitation, potential evapotranspiration), rainfed cropland excluded in arid areas, limited water resources
(Schulze et al., 2021)	Turkey/national	Land degradation	Climate variables affecting land suitability—dynamic (annual temperature, annual precipitation, potential evapotranspiration), rainfed cropland excluded in arid areas, irrigated cropland has higher suitability in semi-arid areas

agricultural activities. Finally, in reality, available water resources would be even more constrained than in our study, as the crops' irrigation water requirements will increase due to future climate change, meaning farmers would need more water with existing or decreased water resources (Fader et al., 2016).

In this study, we focused on climate change impacts on the agricultural sector. Climate change impacts the whole earth system, making it necessary to study the influence on nonagricultural sectors as well (Harrison et al., 2016; Popp, Rose, et al., 2014). Ideally, land use models would consider how different sectors compete for the same land resources and how future climate change might impact them (Popp, Humpenöder, et al., 2014; Smith et al., 2010). Climate change impacts on forests and other tree-dominated land systems (e.g., multifunctional mosaics that provide a considerable amount of food in the Mediterranean region) go beyond changes to their spatial distribution, as climate change might increase tree mortality (Allen et al., 2010), something available data cannot yet capture.

While we tried to include the dynamics of climate change impacts through time, by operating on an annual temporal scale, we were not able to include seasonal changes. In the Mediterranean, future warming and drying is however expected in the warmer seasons (Giorgi & Lionello, 2008). Additionally, by using gradual changes to our climatic variables, we were unable to capture extreme events, such as droughts and heatwaves, that would present shocks both to regional food security and could indirectly impact other human (land-use) activities by potentially leading to socioeconomic disruptions (see for example Kelley et al., 2015). Therefore, it is unlikely that our model representation is underestimating the climate impacts that will be faced in reality. Moreover, we assumed that the statistically derived relationships between the climate variables and land systems under future climate change remain the same as under the current conditions. The relations between the climate conditions and the land systems are based on the current land use pattern that has been shaped over a very long period. As the future conditions are likely to be different from past conditions, this introduced an uncertainty in the estimation of our land system suitabilities.

Finally, we did not study potential feedbacks due to future land system changes. The future extent of adaptation will be affected by changes to soil quality, land and water resources, and degradation of ecosystems (Lambin & Meyfroidt, 2010). These feedbacks are likely to be exacerbated due to climate change and can lead to additional adaptation due to reduced cropland productivity, overgrazing, or availability of water resources. Feedbacks are difficult to quantify, and understanding how responses to land system change influence future land system change remains a significant challenge (Le et al., 2012; Verburg, 2006).

4.4 | Conclusions and future recommendations

We recommend the following measures to improve spatial land use modelling. First, context-specific spatial restrictions based on biophysical limitations are necessary to simulate land use change more

realistically. Some land use types (such as intensive rainfed cropland) might be excluded in specific areas, for example, due to high aridity - despite the possibly high land suitability in the same locations due to market proximity, high population density, or beneficial soil characteristics. The same is valid for not considering limited water resources, which will likely decrease in some areas in the future. This has been demonstrated to lead to overestimation of implemented irrigation and underestimation of cropland intensification in areas where future rainfall will still allow rainfed cropland. This is important as intensification is among most important land use processes as identified both by spatial allocation models (van Asselen & Verburg, 2013) and outlooks on increasing crop production (Mueller et al., 2012). Secondly, spatial allocation has been demonstrated to be particularly sensitive toward expert-based triggered land use change. Decisions on necessary land use change should be complemented with behavioural modelling approaches that better reflect the decisions of individuals and institutions (and their characteristics) to adapt (Arneth et al., 2014; Brown et al., 2017; Magliocca, 2015; Malek & Verburg, 2020; Rounsevell & Arneth, 2011). Generalizing local knowledge is another way to improve global- or large-scale models (Magliocca et al., 2015; Malek et al., 2019; Rounsevell et al., 2014; van Vliet et al., 2016). Moreover, studies using spatial allocation models should evaluate their results in the light of future climate change and climate data used in their studies. This can be done by demonstrating the actual effect of climate change on the results. This way, the users (i.e., policy makers, other researchers) would be informed on the potential uncertainties of the results, particularly when land use scenarios differ in terms of climate change responses and adaptation.

DATA AVAILABILITY STATEMENT

The land use model and land use simulations are available on https://dataverse.nl/dataverse/BETA and www.ivm.nl

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