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Modelling transformational adaptation to climate change among crop farming systems in Romagna, Italy

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ABSTRACT

As the impact of climate change on the agricultural sector has begun to manifest itself in its severity, adaptation planning has come under scrutiny for favoring the preservation of status-quo conditions over more substantial changes. The uptake of transformational adaptations, involving a significant re-structuring of the agricultural system, is however hindered by a lack of assessment tools capable of quantifying the effects of these often more complex, far-reaching, and unprecedented changes. Agent-based models can simulate decision processes and multi-level feedbacks between system components and may therefore illustrate how transformational adaptations emerge and help identify cases where their implementation is necessary and desirable. We explore this modelling potential and aim to quantify (1) how climate change, farmer behavior and water policies may influence strategic adaptation decision-making at the farm-level, (2) the extent to which implemented adaptations represent transformations, and (3) their impact on farm structure and wider socio-ecological change. We investigate these aims through a case study of crop farming systems in the drought-prone historical region of Romagna (NE Italy), integrating insight from stakeholder interviews, local reports, spatially-explicit biophysical data and behavioral theory in the construction of an agent-based model. Results show that, on average, more than half of all implemented adaptations are transformations, thereby requiring important social and financial investments from farmers. The number of implemented transformations is highest in scenarios where drought risk perception among farmers is more widespread, notably in scenarios simulating drier climates, more adaptive behaviors and policies promoting greater water use efficiency. Under higher drought risk perception, farmers are motivated to explore a broader set of adaptations, including those outside of the trajectory determined by their farming strategy. This process particularly favors the implementation of transformational increases in farm size and irrigated area, eventually stimulating farmers to adopt an expansionist strategy. Regionally, these adaptations lead to the smallest decline in agricultural extent with fewest, yet highest profit-earning farmers, largely exacerbating presently occurring trends. Under policy scenarios simulating increased irrigation availability, fewer farmers initially experience drought and therefore perceive a drought risk. Consequently, fewer farmers undertake transformational adaptations and switch from a contractive to an expansive strategy, culminating in a relatively smaller and less profitable agricultural extent despite a larger farmer population. As transformative changes to farming strategy trigger farmers to engage in new path-dependencies, aims of water policies may therefore rebound into unintended effects, emphasizing the importance of accounting for transformational perspectives.

1. Introduction

Growing recognition of the impact and rate of climate change has

shifted the discourse on climate action and drawn increased attention to the development of adaptation plans (Pielke et al., 2007). In 2013, the European Commission published and adopted the "EU Strategy on

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Adaptation to Climate Change", calling on member states to formulate multi-level adaptation strategies and promote adaptation in key vulnerable sectors (Aguiar et al., 2018; European Commission, 2013). The strategy identified the agricultural sector as highly vulnerable to the adverse impacts of climate change. Particularly within southern Europe, where agriculture is most susceptible to increased drought periods, adaptation planning to sustain agricultural productivity, rural livelihoods and ecosystem functioning has been a major subject of inquiry and critique (Berkhout et al., 2015; European Commission, 2013).

A central criticism has emphasized a preference within adaptation planning on initiatives promoting short-term, incremental adjustments over more substantial, transformational, changes (Berkhout et al., 2015; Rickards and Howden, 2012; Vermeulen et al., 2018). While incremental adjustments are suited to farmer experientially-guided decision-making, they often maintain the defining properties of an existing system, and may therefore insufficiently address the unprecedented challenges posed by climate change (Vermeulen et al., 2018). Incremental adjustments are especially unlikely to provide effective results in areas where their potential is already saturated (Kates et al., 2012). In southern Europe, historical expansion of irrigation has resulted in regions where more than 50% of utilized agricultural area is currently irrigated (Eurostat, 2019). With water availability for agriculture expected to decrease due to rising environmental awareness and economic development alongside climatic changes (Iglesias and Garrote, 2015), the long-term sustainability of adjustment approaches aimed at safeguarding on-farm water supply to water intensive crops is increasingly being questioned (Stein et al., 2016).

Transformational adaptation approaches thus require consideration (Rickards and Howden, 2012). Several definitions of such approaches have recently been proposed, primarily defining transformational adaptations as major changes to system components or perspectives which occur when system thresholds are breached (Panda, 2018). To operationalize the concept, Vermeulen et al. (2018) proposed a definition which focuses solely on the outcomes of transformative processes, defining transformational adaptations as those resulting in a substantial redistribution in at least one third of an agricultural system's primary factors of production, outputs or outcomes within a period of 25 years or less. At the farm scale, examples of such transformational adaptation include substantial changes to crop production, (re-)allocation of water resources, on-farm income diversifications and relocation. According to this definition, transformational adaptations can either be autonomously implemented by farmers or externally driven by policy.

The implications of transformational adaptations, as opposed to adjustments, are significant. Transformational adaptations comprise more substantial transaction costs (financial or social) and may be more difficult to reverse and induce maladaptive outcomes as changes to goals or perspectives establish new path dependencies (Rickards and Howden, 2012). Identifying cases where transformational adaptations may be necessary or desirable is therefore important, yet features of nonlinearity, heterogeneity, and inconsistency which characterize farm system transformations complicate this task (Wilson, 2008). In light of this challenge, modelling tools have been proposed as a means to facilitate the exploration of transformational adaptation by illustrating the outcomes of system interlinkages and by providing deductive tools for exploring different strategies (Brown et al., 2017; Holman et al., 2018; Huet et al., 2018). In contrast to commonly used "top-down" global and regional (macroeconomic) modelling studies relying on aggregate information, agent-based models (ABMs) have emerged as particularly suitable models for the comprehensive exploration of adaptation dynamics and transformational change (An, 2012; Berger and Troost, 2014; Huet et al., 2018; Parker et al., 2003; Rounsevell et al., 2012). The potential of ABMs lies in their capacity to (1) simulate individual decision-making, capturing the influence of different strategic farming goals and perspectives, and (2) address interlinkages, accounting for multi-scalar drivers and temporal feedbacks between individuals and their institutional and biophysical contexts (Matthews et al., 2007; Wens et al., 2019).

By means of a case study, we hereby utilize this modelling potential for the exploration of transformational adaptations to water scarcity by simulating strategic decision-making at the farm-scale. Specifically, we construct an ABM with the aim of (1) quantifying how future climate conditions, farmer attitudes and values, and local water policy discourses influence adaptation decision-making at the farm-level, (2) evaluate the extent to which implemented adaptations represent transformational cases by adapting the definition of Vermeulen et al. (2018), and (3) quantify the implications of transformational adaptation for farm structure and socio-ecological change. We develop the ABM by integrating behavioral theory with findings from stakeholder interviews and local reports addressing crop farming systems in Romagna, a drought-prone agricultural area comprising part of the administrative region of Emilia-Romagna (NE Italy), displaying trends of increased irrigation, multifunctionality and scale enlargement characteristic of the broader national and European context (Rivaroli et al., 2017). Following a case study description in Section 2, we outline the processes of model characterization (Section 3.2) and parameterization (Section 3.3). Section 3.4 presents an overview of the climate, behavior and water policy scenarios explored, and is followed by a presentation and discussion of the modelling results.

2. Case study description: agriculture and irrigation management in Romagna

Romagna (6′380 km^2), a historical region, administratively within the region of Emilia-Romagna (Fig. 1), harbors a competitive and diverse agricultural landscape characterized by permanent, horticultural and cereal crops (Consorzio di Bonifica della Romagna, 2016; Regione Emilia-Romagna, 2017d; Weltin et al., 2017). The area is one of Italy's most important with regards to the adoption of on-farm income diversification activities (Henke and Povellato, 2012). Romagna is drought prone due to low precipitation rates and streamflow from the Apennines (Munaretto and Battilani, 2014). This triggered the construction, beginning in 1955, of the "Canale Emiliano-Romagnolo" (CER), a diversion canal originating from the Po River. Subsequent transitions from rain-fed to irrigated agriculture, favored by higher crop prices and infrastructural investments, have however in some areas disproportionately strained water resources, sparking concerns for desertification (Benini et al., 2010).

Irrigation water in Romagna is largely managed by two public-private consortia, notably the Land Reclamation and Irrigation Consortium of Romagna (LRIC-R) and Western Romagna (LRIC-WR) (Table 1, Fig. 1). The LRIC are tasked with setting water prices, planning new water distribution systems, handling permits for water usage, and developing and implementing emergency drought action plans (Munaretto and Battilani, 2014). Irrigation water in LRIC districts is sourced and distributed primarily through artificial, open canals largely fed by the CER and distributing (unmetered) water to farms on demand. Additional distribution systems include metered, pressurized pipes primarily linked to the CER and to water retention basins managed collectively by farmers. Insufficient outreach of secondary canals from the CER in the eastern plains has meant groundwater withdrawals from wells through private concessions have remained prevalent in these areas despite severe ground subsidence (Table 1) (Regione Emilia-Romagna, 2015).

Present irrigation infrastructure will not be able to meet future irrigation water demands under current crop production schemes (Bagli, 2017). Historically, measures have focused on the expansion of LRIC-managed metered pressurized pipe distribution networks. Attempts to curb irrigation water demand and maintain ecological river flows have however increasingly gained ground under pressure from environmental groups (Munaretto and Battilani, 2014), mirroring drought policy discussions taking place at the supra-national level (Stein et al., 2016).
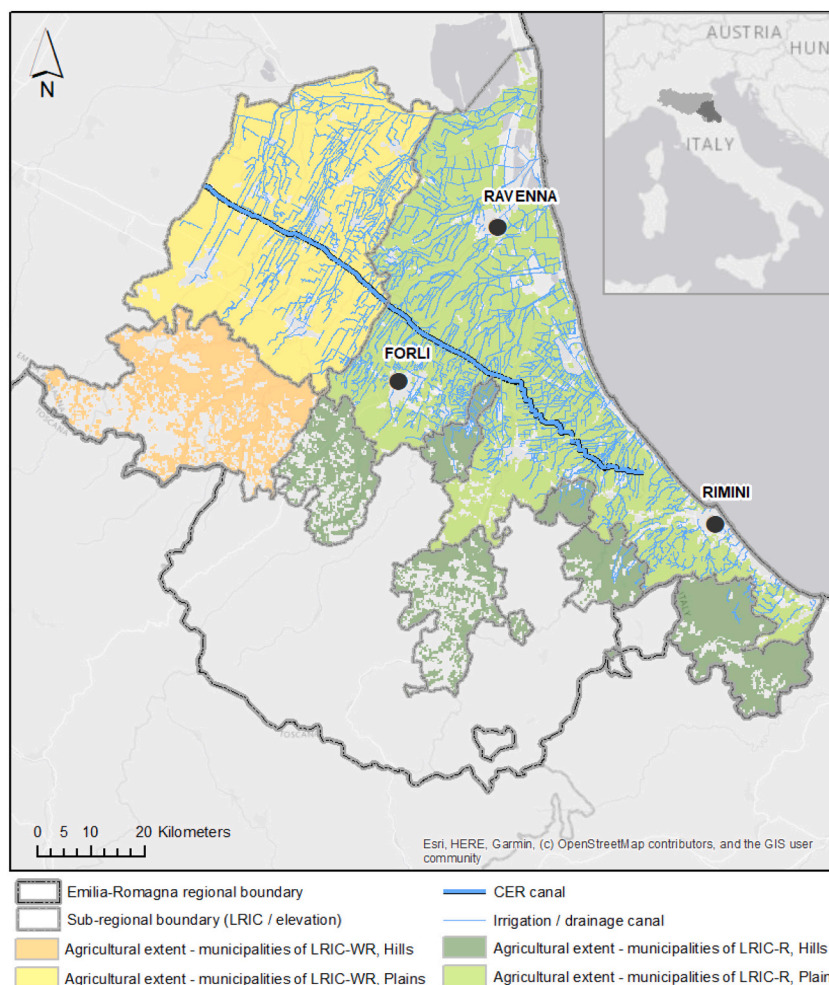
Fig. 1. Characteristics, location, and subdivision of our case study area within the Emilia-Romagna region (NE Italy). The case study extent is defined by the 58 municipalities in the Emilia-Romagna region under management of the LRIC of Romagna or Western Romagna with predominantly crop-based farming systems (SI1) (ESRI, 2020; European Environment Agency, 2016; Regione Emilia-Romagna, 2017a, 2017b, 2017c).

Table 1
Past and present farming and irrigation characteristics in the four sub-regions of Romagna, defined and classified by all municipalities whose territories at least partly fall under either local irrigation management authority (if both are present in the municipality, the LRIC with the biggest territorial coverage is selected) and elevation class (below and above 100 m elevation) (Istituto Nazionale di Statistica, 2010).

Characteristic	Year	LRIC-West Romagna		LRIC-Romagna	
		Hills	Plains	Hills	Plains
No. of farms	2010	1807	7320	5544	10,731
	1982	2994	13,719	10,277	22,200
Utilized Agricultural Area (ha)	2010	23,519	107,106	63,792	96,561
	1982	32,497	112,790	80,979	104,858
Irrigated farms (%)	2010	55	70	47	65
	1982	11	24	8	25
Irrigated farms using micro-irrigation systems (%)	2010	88	72	51	47
	2000	72	53	23	22
Irrigated farms sourcing water through private concessions (%)	2010	94	58	92	64
	2000	98	96	92	92
Irrigated farms sourcing water through LRIC (%)	2010	3	40	5	32
	2000	0	3	1	5

3. Methods

We operationalized the Modelling Human Behavior (MoHuB) framework of Schlüter et al. (2017) to define the model entities and processes. Three principal entities are outlined in the framework: an *external* social and biophysical environment within which agents make decisions, *individual* agents with their goals, values, and assets, and a set of *perceived behavioral options* which agents may choose to perform. These entities interact through three consecutive processes representing adaptation decision-making: farmers first update their characteristics based on their *perception* of changes to the external environment, they then *select* which adaptation to implement based on its capacity to meet their goals, and lastly *implement* the selected adaptation with repercussion to internal and external characteristics.

The following sections outline the process of model characterization and parameterization and present an overview of the model. In Sections 3.1–3.2, we outline how interviews with key informants and farmers alongside the analysis of local literature were undertaken to characterize the model's entities and processes. These findings were integrated with behavioral theory on adaptation decision-making to further structure the characterization of decision processes. In Section 3.3, we detail the parameterization of model variables, which used interview results, local literature, and secondary biophysical and socio-economic farm data. The model was run under different scenarios, reflecting possible future changes to external variables (climate and water policy) as well as

internal characteristics (farmer attitudes and values) (Section 3.4).

3.1. Interview procedure and analysis

We performed open interviews with 14 key informants (public officers of local LRIC, production and service cooperatives, a local agrarian consortium, and a farmer union each representing at least one of the provinces of Ravenna, Forli-Cesena, and Rimini). The selection of key informants was guided by the institutional analysis of Munaretto and Battilani (2014). Each informant also served as an entry point for farmer interviews. 53 semi-structured interviews were conducted with farmers, 36 with cooperative members and 17 with non-cooperative members interviewed at weekly farmer markets in Faenza, Cesena, and Rimini, aiming to capture a diversity of perspectives from smaller farms. Interviews with key informants and farmers addressed past and expected future adaptations and aimed to identify external and internal (socio-cognitive) barriers and enablers. Interviews at farmer markets addressed these same sections but followed a shorter format to accommodate for the time availability of farmers in this context.

Qualitative content analysis of interview transcripts was undertaken following Flick (2014). The coding frame aimed at model characterization following the MoHuB framework, beginning with the identification of structural entities and following with the identification of relations between external entities and farmer decision-making, reporting perceived drivers or barriers to adaptation. Interviews were additionally analyzed by means of descriptive analysis to support model parameterization (further details in SI2 and SI3).

3.2. Model overview and characterization

3.2.1. Model overview

The ABM explores the effect of changing climate, water policy and farmer attitudes and values on adaptation decision-making by individual farmers in Romagna. A farmer's annual decision-making process begins with a perceptual phase: farmers establish whether they perceive a risk of future drought damage and whether they perceive a possibility to adapt. This process follows the framework of Grothmann and Patt (2005) based on the Protection Motivation Theory (Maddux and Rogers, 1983), which defines risk and adaptation appraisal as the primary perceptual processes guiding adaptation decision-making. Farmers' drought risk perceptions depend on their concern for climate change and past experiences of drought. If a risk is perceived, the farmer will proceed to evaluate possibilities for adaptation, and eventually implement the adaptation with the highest utility, i.e. the adaptation which best fulfills a farmer's economic and strategic goals. The scale and nature of implemented adaptations is evaluated to determine whether these represent transformational cases and whether they involve a change in production type and strategic goals. With each annual time-step, the model records the (transformational) adaptations implemented by farmers, as well as the ensuing changes to Romagna's farm structure, agricultural revenues, and irrigation consumption.

3.2.2. Entities

Details on the model entities characterizing the ABM are provided in Table 2. These were identified through the analysis of interviews and local literature, and structured as follows (SI2 provides details on model characterization and outlines which influential variables were excluded from the model):

- *External environment*: influential external variables were categorized as either economic, policy, biophysical, demographic, or social. Two water policy trajectories were identified and primarily sourced from local reports and literature. These trajectories aim to either expand irrigation supply through collectively managed LRIC sources and improved distributional efficiencies (Zavalloni et al., 2014), or to limit irrigation demand by restricting the expansion of water

Table 2
– Overview of core model entities and attributes (respective parameterization references are listed in Table SI4); policy attributes are largely absent as these principally operate by influencing other attributes (e.g. market prices) depending on the scenario explored (see Section 3.4).

Model entity	Attributes
External environment	
Biophysical	Precipitation; Reference evapotranspiration; River discharge; Watershed boundaries; Crop suitability; LRIC expansion suitability
Demographic	Rate of newcomer farmers
Policy	Minimum number of farmers required for the investment in new collective LRIC water resources; River discharge threshold for cessation of irrigation withdrawals
Economic	Cost of land; Crop specific conventional production profits (based on revenues and costs); Crop specific deepening production profits (based on revenues, costs, and subsidies); Broadening profits (based on revenues and costs); Cost of crop conversion; Cost of purchasing/upgrading irrigation systems; Cost of constructing new LRIC water sources; Cost of converting farm to broadening activities; Cost of irrigation water
Individual characteristics	
Farmer assets	Age (class); Presence of successor; Savings; Cooperative membership
Farmer goals	Farming strategy (and respective adaptation preferences); Aspired profits
Farmer values & attitudes	Climate change concern; Water conservation (willingness to invest in water saving crops and irrigation systems); Environmental conservation; Autonomy; Openness to change (strategy and/or production); Drought risk perception
Farm	Field composition; Crop production type; Size; Irrigation status; Annual irrigation withdrawals; Annual farm profits (based on revenues and costs); Annual estimated Return on Investment from each adaptation; Annual estimated utility of each adaptation; Neighboring fields
Field	Ownership status; Size; Field production (crop and conventional vs. deepening management); Rotation plan; Crop water needs factor (kc); Duration of crop growth stages; Cumulative soil wetness; Drought damage; Field irrigation system and efficiency; Field irrigation water source and efficiency; Field irrigation water availability; Annual irrigation requirements; Annual irrigation withdrawals; Field profits (based on revenues and costs); Field standard output; Neighboring fields
Perceived adaptation options	
Perceived adaptation options	Increase farm size; Decrease farm size; Expand irrigated area; Upgrade irrigation efficiency; Adopt a diversification strategy (deepening); Adopt a diversification strategy (broadening); Change crop production

demanding crops, introducing withdrawal quotas, subsidizing efficient irrigation systems and increasing awareness on water use efficiency (Bagli, 2017; Regione Emilia-Romagna, 2009). Economic factors were stated in the interviews and referred to farm finances (Table 2). Influential biophysical factors referred primarily to climate impacts and irrigation water accessibility, demographic factors related solely to the entry of new farmers in Romagna, while social factors referred to processes of farmer imitation or indirect competition for resources. These social factors are not captured in the model as "external" entities but are instead represented through processes of farmer-to-farmer interaction.

- *Farm(er) characteristics*: farmer goals were defined as economic and strategic, and identified in statements referencing different profit ambitions and farming strategies. Aspirations for profit changed from maximizing to satisficing (Gotts et al., 2003) with decreasing farm size, increasing age and lack of successorship, resulting in a lower propensity to adapt. Due to the model's resolution being too coarse to capture smallholder farmers, only age and presence of successor are considered in the model's estimation of aspired profits. Farming strategies describe a limited set of cohesive adaptations. Stated preferences revealed a differentiation between pursuing

diversifying and non-diversifying orientations, resulting in the identification of four different strategies. Two non-diversifying strategies were identified and termed "expansive" and "contractive" (Wheeler et al., 2013), respectively illustrating strategies centered on increasing or decreasing the use of agricultural resources. The two identified diversifying strategies were termed "broadening" and "deepening" (Ploeg and Roep, 2003). A deepening strategy aims to increase the value of agricultural produce (e.g. direct sale, organic certification, PGI production), while a broadening strategy aims to increase farm-income through on-farm non-agricultural activities (e.g. agri-tourism, care farming) (Rivaroli et al., 2017). Qualitative analysis of interview results additionally revealed a relation between a farmer's climate change belief, drought risk perception and willingness to adapt. It also outlined how farm characteristics and farmer values influence perceived ability to implement adaptations (Table 3). Influential farmer values were categorized into four dimensions referencing the Theory of Basic Values (Schwartz, 2012), notably: openness to change (vs. tradition), environmental conservation (i.e. self-transcendence, vs. self-enhancement), collaboration (vs. autonomy) and ambition (reflected within different aspired profits) (Table SI2).

- *Perceived adaptation options*: we classified the adaptive actions identified through interviews into seven adaptations: increasing or decreasing farm size, expanding irrigated area, upgrading irrigation efficiency, adopting a diversification strategy (deepening or broadening), and changing crop production. These drought adaptations deliberately incorporate a broad set of actions relating to general farm management and structure, reflecting the reality of farmer decision-making which incorporates decisions on adaptation within broader, often strategic, risk management considerations (Amadou et al., 2018).

The adaptations considered in the model largely represent incremental adaptations which may result in transformational change depending on their rate and scale of implementation. We adapted the definition of Vermeulen et al. (2018) and categorized adaptations as transformational if they resulted in an increase or decrease of at least one third of inputs within the simulated time-frame (for irrigation inputs or land), or a change to the production type which comprises two thirds of standard output (this ratio is set to match the classification of production types used at initialization (European Commission, 2017)) (Table 3). We additionally identify adaptations which involve a change in pursued strategy (i.e. goals) as transformational. In any given year, farmers pursue only one of the four possible strategies. This pursued strategy can change either following the unprecedented uptake of a diversification strategy or following transformational change to inputs or scale which will automatically trigger the uptake of an expansive or contractive strategy (depending on the direction of change). For example, transformational increases in the use of irrigation water or farm size will trigger farmers to adopt an expansive strategy. Changes to farming strategies reflect the re-orientation of goals and establishment of new path dependencies following the evaluation of new, successful adaptations by farmers (Sutherland et al., 2012). If these adaptations no longer prove successful in the future (i.e. will result in drought damage), the farmer will be more inclined to change strategy again and explore new adaptations (see sub-model 2). Farmers who chose to stop pursuing a diversification strategy will not cease their diversification activities but will simply stop pursuing future actions which align specifically with the diversification strategy.

3.2.3. Processes and scheduling

The ABM is structured around three principal "sub-models" (Fig. 2), and simulates annual decision-making across an initial population of 8584 farmers throughout 33 irrigation seasons (March 1st to October 31st), representing the years 2017 to 2050 as follows (see SI4 for a comprehensive description following the Overview, Design Concepts,

Details and Decisions (ODD+D) protocol of Müller et al. (2013)):

- *Sub-model 1 – demographics and soil-wetness*: farmers update their age at the beginning of each year and, upon retirement, choose to pass their farm onto a successor, sell it to a newcomer farmer or place it on sale on the market. At each 10-day time-step throughout the irrigation season, precipitation, evapotranspiration, the crop water needs factor (kc) and irrigation input values are updated and used to calculate cumulative soil-wetness. We assume the maximum potential irrigation volume available within each LRIC district is distributed fully and equally throughout the season. Irrigation amounts are only changed as a result of (1) policy changes, depending on the policy scenario (Section 3.4), (2) changes to irrigation system efficiencies, or (3) as a result of critical drought periods, determined by low discharge levels in the Po River triggering the cessation of all irrigation withdrawals. At the end of the season, farmers evaluate whether fields have received sufficient water or have experienced a deficit resulting in production damages, and re-open any former private water sources present on damaged fields.

- *Sub-model 2 – adaptation decision-making*: at the end of the irrigation season, farmers evaluate whether to engage in adaptation by updating their perceptions of drought risk and possibilities for adaptation. Drought risk perception is based on the perceived probability and severity of drought occurrence (Grothmann and Patt, 2005), parameterized by a farmer's climate change concern and whether their aspired agricultural profits have not been met in the past year following drought damage. Older farmers without successors have lower aspired agricultural profits, and act as satisficers rather than profit maximizers. The two determinants of drought risk perception hold equal weight, and result in a maximum potential drought risk perception value of 1. Farmers with a drought risk perception value of 0 do not engage in any adaptation. Next, farmers evaluate adaptations by estimating each adaptation's costs, efficacy and alignment with their strategy (Grothmann and Patt, 2005). This is undertaken by calculating the expected utility of each possible adaptation by evaluating (1) its expected "return on investment" (ROI) (i.e. estimated annual profits divided by estimated investment costs, normalized across all adaptations to hold a value between 0 and 1), and (2) whether the adaptation does or does not align with the farmer's own pursued strategy (respectively assigning a value of 0.5 or 0) (Table 3). Farmers select the adaptation with the highest utility yet will only implement this adaptation if its utility value, combined with their drought risk perception value, surpasses a threshold. The threshold is lower (equal to 2) for farmers who value openness to change, resulting in farmers with a higher threshold (equal to 2.1) only engaging in adaptation if their drought risk perception is high and if an adaptation both matches their strategy and represents a high ROI.

- *Sub-model 3 – implementation of adaptations and feedbacks*: farmers who chose farm expansion, water source expansion, or crop change perform further feasibility checks, e.g. by ensuring affordable land is available for sale within the neighborhood (defined by a neighborhood radius of 2.2 km from the farm). If obstacles are present, the farmers do not implement the selected adaptations, nor do they not opt for the second-best adaptation option in terms of estimated utility. All adaptations are re-considered by farmers in the following year under potentially more favorable circumstances. Farmers who do not face further obstacles, or have chosen to shrink farm size, upgrade their irrigation systems or engage in diversification, implement their selected adaptations, and consequently update their internal characteristics. Following the implementation of adaptations, the model calculates if the adaptations implemented by farmers represent transformational cases, and eventually updates the farmer's production type and strategy (Section 3.2.2). Farmers only *pursue* one strategy at a time and will maintain any diversification activities when changing towards an expansive or contractive

Table 3

Adaptation-specific internal and external variables which directly moderate the estimated utility of each adaptation or constrain its implementation. The transformational potential of each adaptation is also illustrated.

Adaptation	Potential for transformation	Moderating variables			
		External	Internal (assets)	Internal (values & attitudes)	Internal (goals)
Buy land	-Scale & input (>1/3 increase) -Strategy change (expansive) -Production type change	Land availability; land price; crop profits	Savings; field crop production	Openness to change (production)	Expansive strategy
Sell land	-Scale & input (>1/3 decrease) -Strategy change (contractive) -Production type change	Crop profits	Field crop production; ROI of other adaptations		Contractive strategy
Expand irrigation	-Input (>1/3 increase) -Strategy change (expansive)	Availability of farmers interested in collective investment; building, irrigation system & water costs; crop profits; LRIC expansion suitability	Savings; cooperative membership; rain-fed area & production		Expansive strategy
Invest in efficient irrigation	-Input (>1/3 decrease) -Strategy change (contractive)	Price of water; irrigation system cost	Savings; irrigation (efficiency, area, volume, metering) cooperative membership	Water conservation (irrigation)	Contractive strategy
Change crop production	-Scale & input (>1/3 increase/decrease) -Strategy change (expansive/ contractive) -Production type change	Crop suitability; crop profits; crop conversion costs	Savings; field crop production; irrigation	Water conservation (crop); openness to change (production)	Expansive & deepening strategies
Start deepening	-Strategy change (deepening)			Environmental conservation; autonomy	Deepening strategy
Start broadening	-Strategy change (broadening)	Broadening conversion costs	Savings; farm economic size		Broadening strategy

strategy. The yearly model run ends with an evaluation of changes to Romagna's annual agricultural production and irrigation water consumption, alongside the implementation of crop rotation plans.

3.3. Model parameterization under baseline conditions

The ABM was developed in NetLogo version 5.3.1 using the GIS and CSV extensions (Wilensky, 1999). The model reads spatially-explicit information on field boundaries, crop production, farm location, irrigation water sources, available irrigation volumes, and climate data. We combined the CORINE-2012 dataset (European Environment Agency, 2016) (for areas >100 m elevation) to the more detailed, regional, iCOLT-2017 dataset (Arpae Emilia-Romagna, 2017) (available only in areas <100 m elevation) to identify the extent of agricultural crop production. We artificially generated field boundaries to reflect the number of fields in each of the 58 municipalities covered by the model's extent, following the most recent agricultural census (Istituto Nazionale di Statistica, 2010) (overview of municipalities in SI1). A minimum of 5 ha was used to account for model computational speed. Fields within the CORINE-2012 extent were randomly assigned crop classes from the iCOLT nomenclature to match the share of municipal agricultural land occupied by each crop according to the census. The census was also used to add a nut tree class and split the "summer crops" class into 4 subclasses (high and low water demanding grains and high and low water demanding vegetables), as these were identified as significant and distinctive classes in interviews. In total, 18 different crop classes were considered. Locations for the 8584 farmers in Romagna were randomly generated within each municipality, matching the number of municipal crop-based farmers from the census, with municipal fields randomly assigned to a farmer ID. The location of private water sources (i.e. wells or on-farm basins) was estimated from census data on the share of municipal irrigated area by water source and share of municipal

irrigated area by crop type. LRIC irrigation districts (representing either pressurized pipe or open canal systems) and respective water capacities were derived from the public plans and reports of both LRIC, while volumes for private sources were identified in census tables outlining crop-based irrigation needs used to determine concession volumes.

Ensemble climate model data (Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5) on daily precipitation, mean river flow and mean temperature from January to October for the years 2017–2050 was downloaded from the SWICCA project (www.swicca.eu) at catchment resolution (SI3). Reference evapotranspiration was calculated according to the Turc equation (Turc, 1961). River flow data was taken for the locality where water from the Po River is diverted to the CER. A discharge value of 200 m³/s was used as the threshold below which water diversion stops (consistent with local drought action plans). The model combines climate variables with temporal single crop coefficient (kc) values (Allen et al., 1998) to determine "soil wetness". Kc-values adjust reference evapotranspiration based on crop transpiration and soil evaporation characteristics. The soil wetness threshold below which crop yield declines was based on the local data and methodology outlined in Bagli (2017). In keeping with this methodology, we set the soil wetness value at 0 with the beginning of each calendar year, proceeding with the computation of cumulative soil wetness for the months of January and February prior to the start of the irrigation season.

Revenues, running costs and investment costs for farm actions were derived from the European Commission's Farm Accountancy Data Network (FADN) and Eurostat databases, agricultural pricing indexes for the Emilia-Romagna region, grey and scientific literature on water pricing, and records of subsidized projects coordinated by authorities of the Emilia-Romagna region and funded by the EU's Rural Development Program. Investment costs and annual profits for deepening activities were based on those for organic farming, while costs and profits for agri-tourism were used to parameterize broadening activities. Farmer values
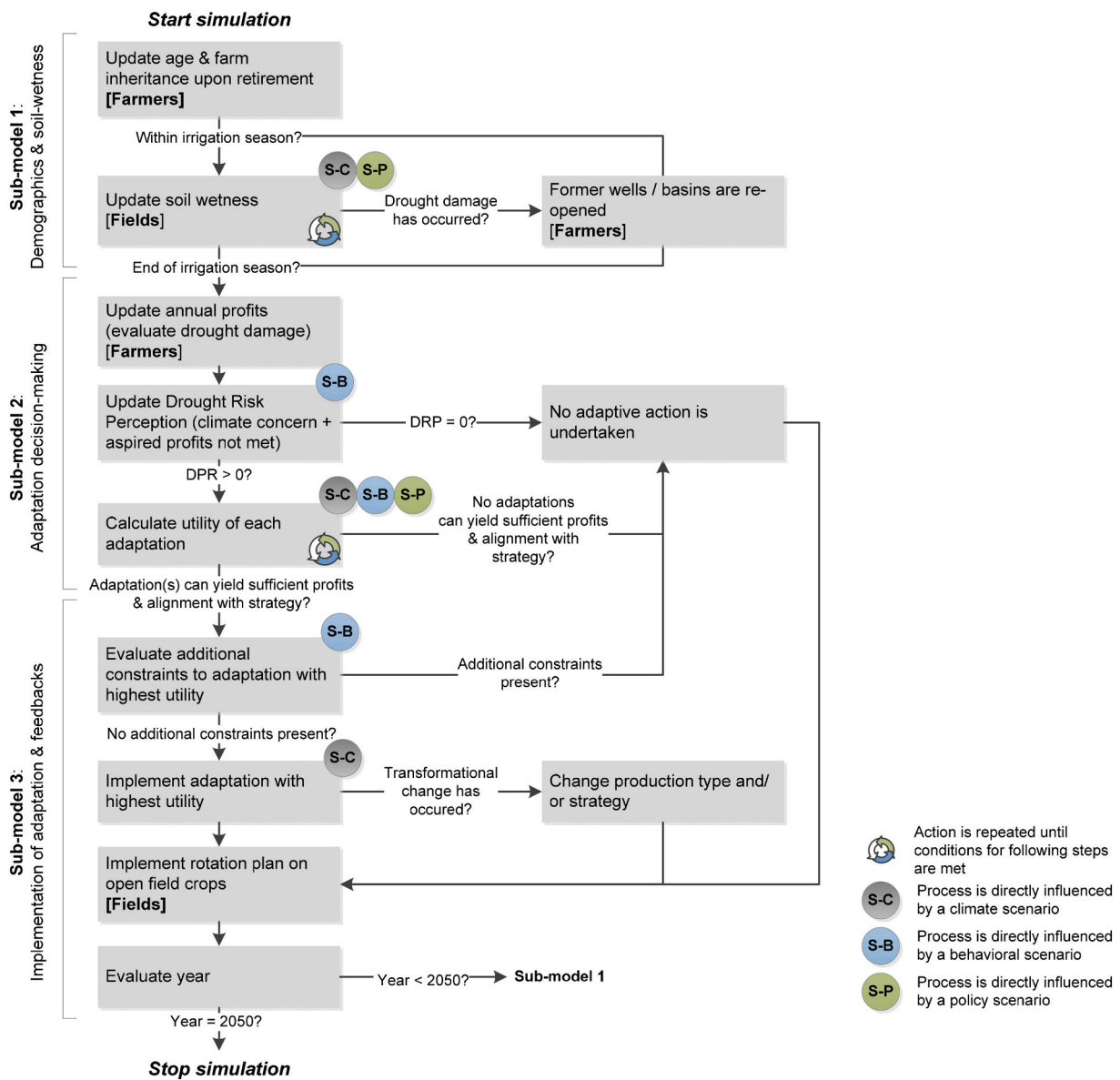
Fig. 2. Overview of primary processes undertaken by fields and farmers chronologically throughout a yearly model run. Points of influence are illustrated for each scenario group (climate, behavior, and policy).

and strategies were distributed across the agent population by applying frequency distributions from our interviewed sample. Farming strategies were assigned according to their distribution within the four farm production types (permanent crop specialists (39%), horticultural specialists (2%), field crop specialists (41%) and mixed cropping farmers (18%)), as production type was deemed the most important determinant of diversification in the local analysis of Rivaroli et al. (2017). The interviews revealed that deepening and expansive strategies were the most frequently implemented (respectively by 51% and 32% of farmers), followed by broadening (17%) and contractive (16%) strategies. Values were assigned according to their interview distributions across both a farmer's strategy and production type. Most farmers were concerned about climate change (89%) and valued openness to change (59%). Water conservation values and openness to change production were assigned from distributions across the total interview sample. A detailed overview of the derivation of input datasets, assumptions in the parameterization process, and calibration procedures is provided in SI3.

3.4. Scenarios and sensitivity analysis

Climate change scenarios provide baseline settings using the parameter values outlined in Section 3.3. We considered climate conditions under RCPs 2.6, 4.5 and 8.5 (respectively representing low, medium and high greenhouse gas emission scenarios (van Vuuren et al., 2011)).[1] Within each climate scenario, behavioral and water policy scenarios were independently explored (i.e. without interacting with one another) and defined as follows (details in Table 4):

- *Behavioral scenarios*: the effect of changing farmer attitudes and values across the population of farmers is explored to scope the potential of behavioral changes alone in driving transformational adaptations. These scenarios, termed most adaptive (MA) and least

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[1] RCP 2.6 has the highest frequency of critical drought level events (i.e. low discharge levels in the Po River), as well as frequency of monthly cumulative precipitation periods occurring below the historical median (1961–2016, April-October period) throughout the simulation period (2017–2050)

Table 4

Changes to parameter values with respect to baseline (B) conditions under the two behavior and water policy scenarios. Behavior and water policy scenarios were explored independently (i.e. throughout separate model runs) under both low (L) and high (H) bound conditions. These rules or values are implemented at model initialization.

Model variable	Behavior scenarios				Policy scenarios			
	MA (L)	MA (H)	LA (L)	LA (H)	RD (L)	RD (H)	ES (L)	ES (H)
Probability unconcerned farmers become concerned about climate change	25%	75%	0%	0%	25%	75%	0%	0%
Probability concerned farmers become unconcerned about climate change	0%	0%	25%	75%	0%	0%	0%	0%
Probability farmers not valuing openness to change start valuing openness to change	25%	75%	0%	0%	0%	0%	0%	0%
Probability farmers valuing openness to change stop valuing openness to change	0%	0%	25%	75%	0%	0%	0%	0%
Subsidy for micro-irrigation systems (% cost)	No subsidy	No subsidy	No subsidy	No subsidy	30%	90%	No subsidy	No subsidy
Subsidy for sprinkler systems (% cost)	No subsidy	No subsidy	No subsidy	No subsidy	30%	90%	No subsidy	No subsidy
Subsidy for new LRIC water source (% cost)	60%	60%	60%	60%	60%	60%	75%	90%
Crop conversions allowed based on irrigation water needs (m^3/ha/year)	All permitted	All permitted	All permitted	All permitted	Crops <3000m^3	Crops <2000m^3	All permitted	All permitted
LRIC irrigation quota	No change	No change	No change	No change	Reduction of 25%	Reduction of 50%	No change	No change
Distributional efficiency in open canals (%)	60%	60%	60%	60%	60%	60%	75%	90%

adaptive (LA) behavior scenarios, respectively simulate a population of farmers which is more or less open to change and concerned about climate change. The share of farmers holding either value and attitude is respectively increased and decreased during model initialization.

- *Policy scenarios*: these reflect the two dominant and contrasting policy discourses identified in Romagna (Section 3.2). The ES policy scenario aims to ensure irrigation water supply by (1) improving distributional efficiencies in open canal systems, and (2) further subsidizing the construction of new LRIC irrigation sources. The RD policy scenario aims to reduce demand for irrigation water through both regulation and incentives: (1) the cost of high efficiency irrigation systems is reduced (following subsidies), (2) conversion to

high water demanding crops is no longer allowed, (3) irrigation withdrawal allowances within LRIC districts are reduced, and (4) active norm engagement means more farmers are concerned about climate change.

Behavioral and policy scenarios are run under low (L) and high (H) parameter values, exploring respective possibility spaces (Table 4). A one-factor-at-a-time sensitivity analysis was additionally performed on each scenario parameter and run under the most extreme conditions for each climate, behavior, and policy scenario group. A sensitivity analysis was also run on model parameters for which there was greater uncertainty, i.e. lacked more robust parameterization sources (see SI3). In this case, results are reported for simulations run under RCP 2.6 climate
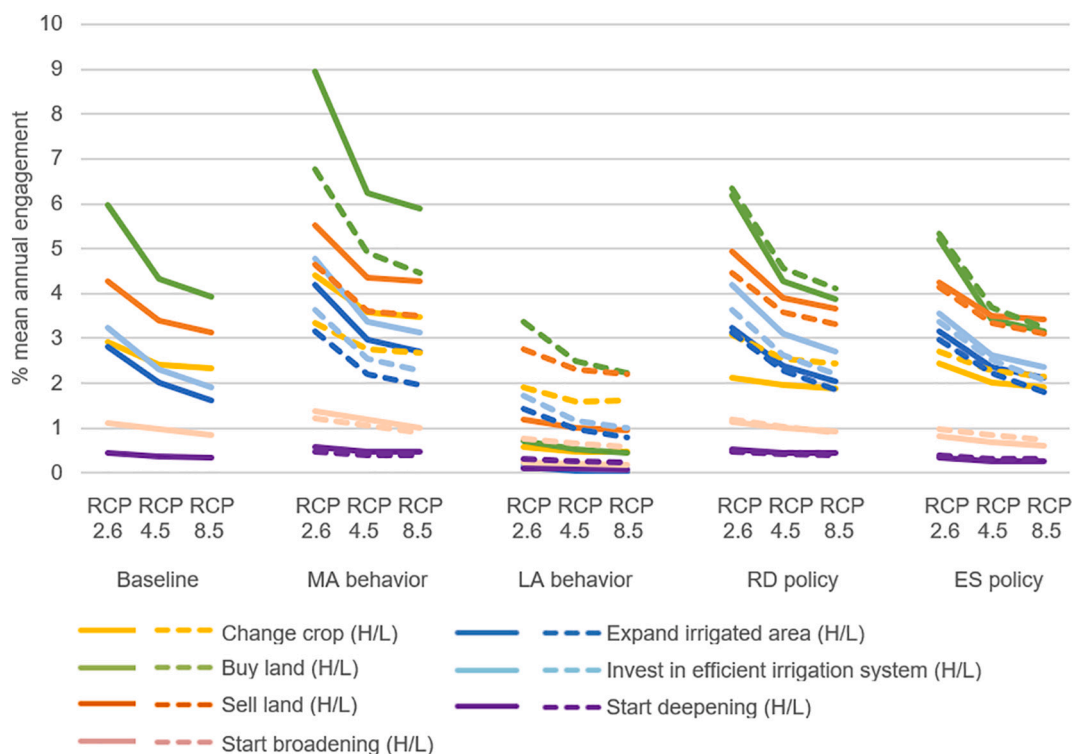
Fig. 3. Mean annual share (%) of farmers engaging in each type of adaptive action throughout a simulation (2017–2050) under scenarios exploring the influence of climate, farmer behavior, and water policy. Dashed lines illustrate results under low bound scenario conditions, while solid lines illustrate results under high bound scenario conditions (Table 4)

scenario conditions alone (ten Broeke et al., 2016; Schouten et al., 2014). All results are based on the averages of 5 repetitions.

4. Results

4.1. Implemented adaptations under climate, behavior, and policy scenarios

All scenarios reveal similar trends in terms of which adaptations are preferred and implemented by farmers (Fig. 3). Under all scenarios, adaptations relating to changing farm size are the most frequently implemented (on average by 4% of farmers annually), commonly followed by adaptations involving irrigation investments or crop changes, and lastly by adaptations involving the uptake of on-farm income diversifications (on average by 1% of farmers annually). Scenario-specific dynamics however additionally emerge:

- *Climate*: Under all baseline climate scenarios, farmers more frequently opt to expand rather than reduce farm size. Drier climates (RCP 2.6) predictably increase the share of adapting farmers, as more farmers witness damages to production and consequently increase their drought risk perceptions and propensity to adapt. Additionally, drier climates favor the implementation of irrigation investments over crop changes.
- *Behavior*: MA behavior scenarios predictably increase the share of adapting farmers when compared to their respective climate baselines, to such an extent that they show the highest engagement out of all the scenarios. The opposite dynamic occurs under LA behavior scenarios. MA behavior scenarios see more frequent engagement in farm size increase than decrease, in contrast to LA scenarios (under high bound conditions) which see more frequent engagement in farm size contraction than expansion.
- *Policy*: RD policy scenarios result in a higher share of adapting farmers when compared to climate baselines, particularly for adaptations involving farm size changes and irrigation investments, with more farmers engaging in farm expansion over contraction. ES policy scenarios also result in a higher share of farmers investing in irrigation than in respective baseline scenarios yet result in an overall reduction to the total share of adapting farmers, with particularly lower values for farm expansion.

Results from the sensitivity analysis (SI5) reveal that changes to a farmer's climate change concern (influencing drought risk perception) are primarily responsible for driving the results in the behavioral scenarios, i.e. the scenarios which result in the greatest changes from baseline conditions. The central role of drought risk perception is also revealed in the ES policy scenario results. Despite ES policy scenarios simulating incentives for adaptation by subsidizing irrigation expansion, the effect on lower drought risk perception following more abundant water supplies results in the overall less frequent engagement in adaptation when compared to baseline results. Scenarios which induce an increase to drought risk perception (i.e. MA behavior, RD policy and drier climates) specifically result in a greater share of farmers engaging in expansive adaptations. This is due to high drought risk perception encouraging farmers to engage in adaptations outside of their pursued farming strategy, therefore witnessing a greater share of farmers embracing the several adaptations with an expansive nature. Conversely, scenarios which induce declines to drought risk perception (i.e. LA behavior and ES policy) result in more farmers implementing adaptations aligned with their strategy, and therefore fewer contractive farmers adapting through farm expansion.

4.2. Consequences for Romagna's agriculture and irrigation water consumption

All scenarios reveal a continuation of on-going processes of farm-

scale enlargement coupled with declining total agricultural area and number of farmers throughout the case study region. Farm-scale enlargement is most pronounced in the MA behavior scenario (high bound, RCP 2.6), which compared to other scenarios sees the smallest decline in regionally cultivated area (−28%) and largest decline to the number of farmers (−67%) (Fig. 4c). Widespread irrigation expansion in MA scenarios (Fig. 5) reduces farm drought damages and enables conversions to higher revenue, and often more water demanding, crops. Consequently, the MA (H) scenario under RCP 2.6 is the only scenario where total regional agricultural revenues do not witness a decline and the share of cropland area is subject to fewest drought damages. Crop conversions result in net increases in regional cultivated area for vineyards, cherries, kaki, apple, plums and mixed fruit orchards (i.e. crops with high profit-earning potential depending on a farmer's conventional, deepening and/or irrigated production) (SI5). Conversions from low-revenue herbaceous crops to higher-revenue permanent crops, coupled with fewer sales of permanent crop fields, result in the regional share of agricultural area comprised of permanent crops increasing from 31% in the first year of simulation to 51% in the final years of both RCP 2.6 and 8.5 simulations. These trends involve considerable increases to irrigation withdrawals, which are on average largest in MA behavior scenarios than in other scenario explorations.

RD policy scenarios have considerably different impacts on Romagna's agricultural sector than MA scenarios, despite similarly promoting adaptation. In RD (H) scenarios, only vineyards witness a net increase in area as changes to high-water demanding crops are restricted (SI5). Despite larger increases to irrigated area than in ES policy and baseline scenarios, RD scenarios witness fewer irrigation withdrawals (SI5) and therefore only hold a small potential to mitigate drought damages when compared to baseline scenarios (Fig. 5). On average, RD policy scenarios see stronger declines to total, regional agricultural revenues than baseline scenarios, yet these remain higher than under ES policy or LA behavior scenarios (Fig. 4c).

The lower frequency of (expansive) adaptation under ES policy and LA behavior scenarios results in larger losses to regional cultivated area, fewer losses to the number of farmers, and less pronounced farm enlargement processes than in RD or MA scenarios. Among all scenarios, the largest declines in regional cultivated area are seen in ES policy scenarios (average of −39%), while the smallest declines to the number of farmers are seen in LA behavior scenarios (average of −50%) (Fig. 4c). Regional agricultural revenues remain worst impacted by LA behavior scenarios, representing the only scenario where irrigation withdrawals decline and where the fewest crop conversions occur, resulting in average total crop revenue declines of −26% especially affecting grains, high water demanding vegetables, and olives (SI5). As a result of higher irrigation expansion in ES policy scenarios than in LA behavior scenarios, drought induced damages to production are more effectively mitigated and regional agricultural revenues see smaller declines (Fig. 5). Compared with baseline conditions, however, ES policy scenarios see stronger declines to regional agricultural revenues despite a smaller share of cropland witnessing drought damage (SI5).

4.3. What role for transformational change?

Fig. 4a illustrates the mean annual share of farmers undergoing different types of transformational adaptation in each scenario, illustrating the frequency with which major change to the use of inputs, scale, production, or pursued farming strategy occurs. Averaged results from all simulated scenarios reveal that while approximately 14% of farmers engage in adaptation annually, 8% of farmers implement adaptations which are considered transformational (SI5), most frequently involving a strategy change or major increases to inputs or scale. All farmers which adapt by starting new diversification activities inherently undergo a transformational adaptation. On average, 44% of annual adaptations through land purchases represent transformational cases, a value which increases to 57% when considering land sales.
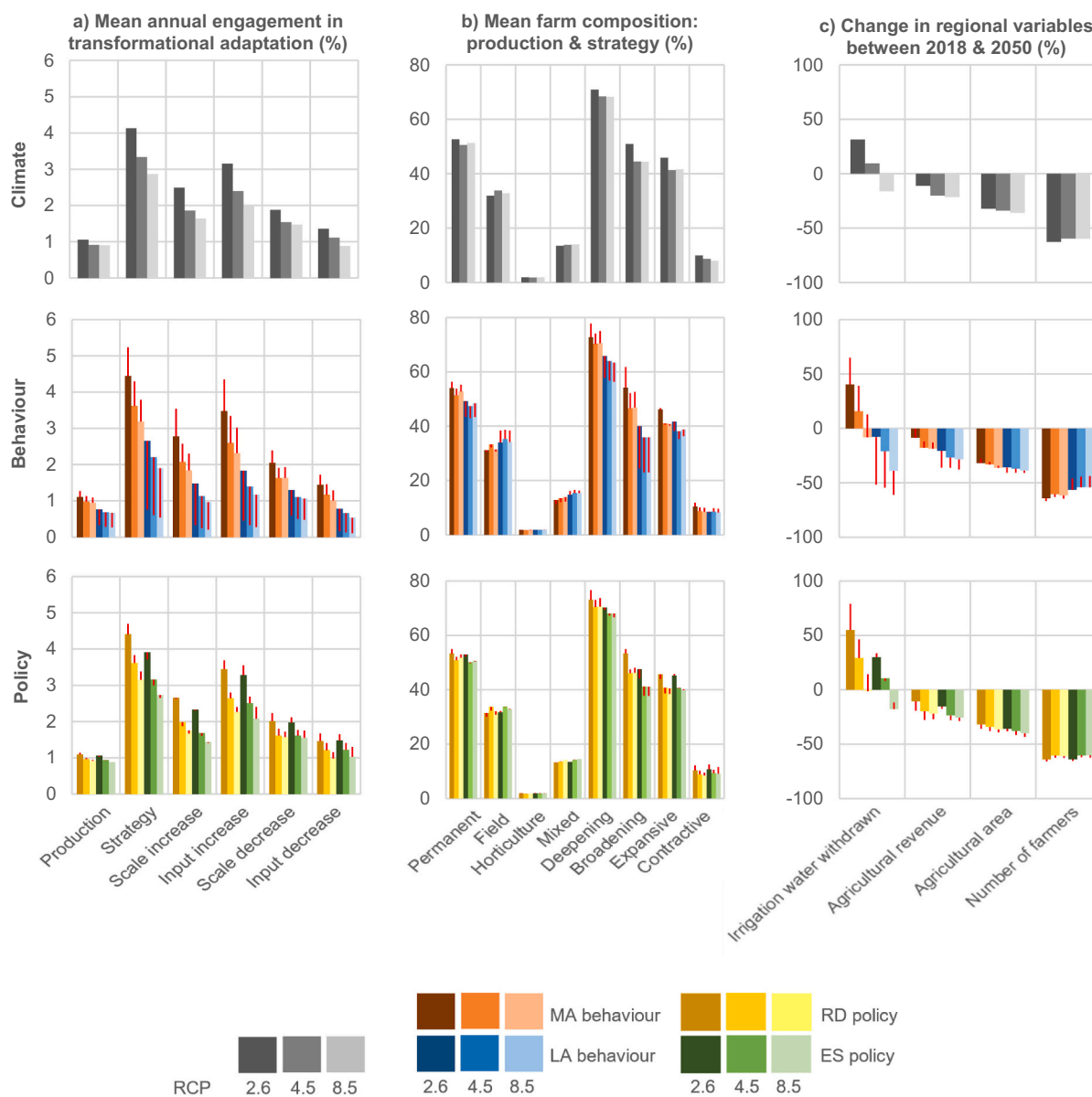
Fig. 4. Influence of changing climate, farmer behavior, and water policy on (A) the annual % mean share of farmers implementing transformational adaptations throughout a simulation (2017–2050), (B) the annual % mean share of farmers belonging to each production type and implemented* strategy throughout a simulation (2017–2050), and (C) the % change in total regional irrigation withdrawals and agricultural production variables, comparing 2050 results with the first year of simulation. The behavior and policy scenarios illustrate results run on lower bound scenario values (Scenario L, Table 4), with red bars illustrating results under the higher bound scenario values (Scenario H, Table 4). Tabulated results are illustrated in SI5. *All farmers pursue only one strategy in any given year, yet diversifying farmers will maintain their diversification activities even if they chose to pursue a non-diversifying strategy. In this case, a farmer is implementing two strategies despite only actively pursuing one. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Approximately 2% of farmers engage in crop change, irrigation system efficiency improvements or irrigation expansion annually, while transformational changes relating to production type change, input increases or input decreases similarly lie in the range of 1–2% (Figs. 3, 4).

These results suggest the different types of transformational adaptation represent a considerable share, and in some cases majority, of adaptations undertaken throughout simulations. As farmers engage in transformational changes to farm size or input use, they will also change their pursued strategy towards an expansive (following resource increases) or contractive strategy (following resource reductions). This establishes new path dependencies, acting as positive re-enforcements which exacerbate regional farm scale enlargement, and further

encourage farmers to pursue expansive adaptations by purchasing land from contractive farmers gradually moving towards farm exit. Contractive farmers represent the least pursued strategy by the end of all scenario explorations, while the share of farmers pursuing expansive strategies increases from 32% to an average of 52% (SI5). Transformations relating to crop changes (although less frequent than those relating to scale) further contribute to scale enlargement trends as these involve transitions towards more input-intensive permanent crops, thereby also promoting the adoption of an expansive strategy. Active farms therefore become, on average, larger and more profitable throughout simulations. Additionally, transformational changes in strategy also relate to the uptake of diversification strategies, which gain
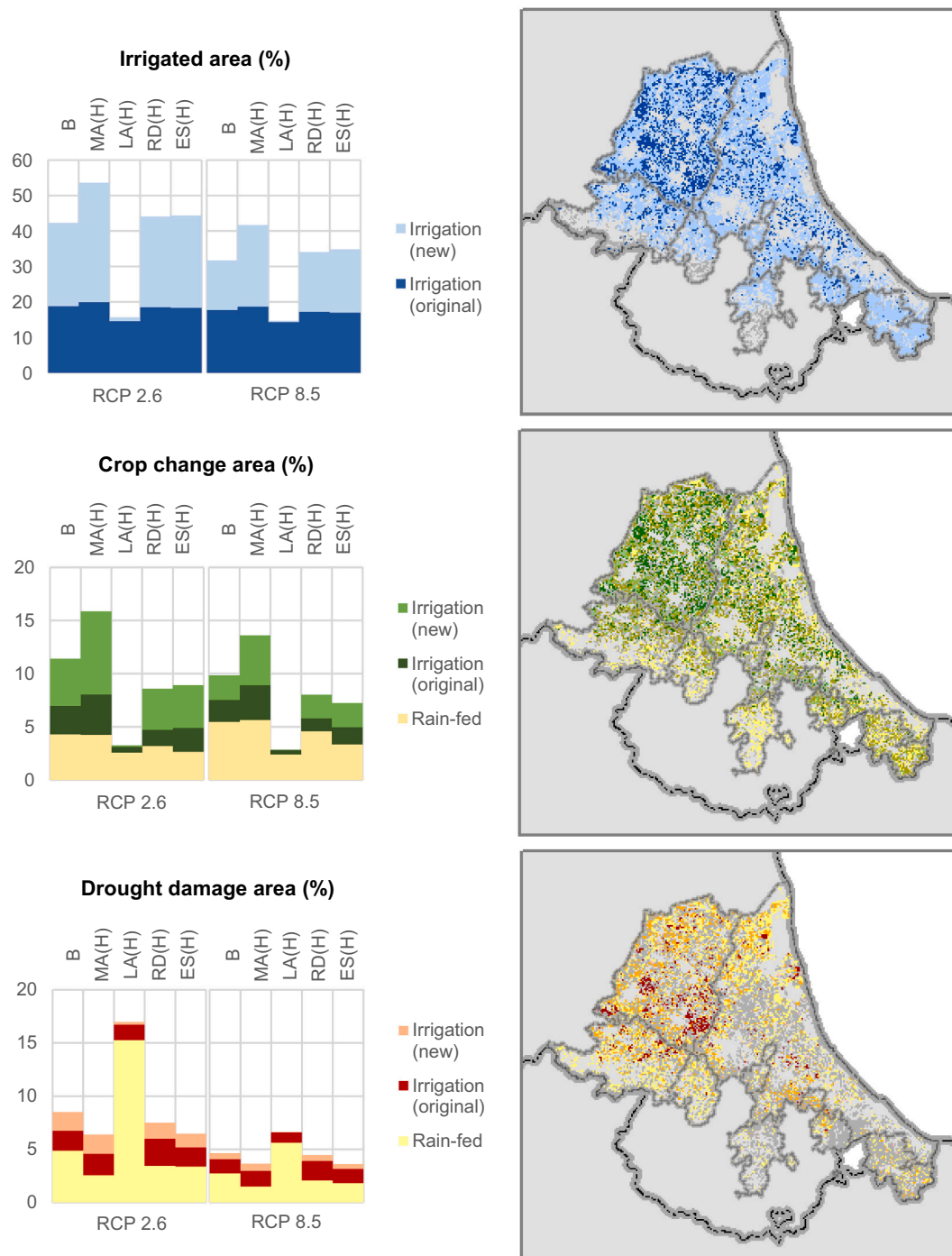
Fig. 5. Influence of climate (B), behavior and water policy scenarios (high bound conditions) on the share of agricultural area witnessing irrigation expansion, crop change and drought-induced damages to production in Romagna. The share of agricultural area is calculated based on the agricultural extent at the end of respective simulations. Drought damaged areas refer to parcels which witnessed drought damages in at least half of the time-steps of a simulation. Maps illustrate the agricultural extent which is affected by at least one scenario (each run for 5 different simulations). All results are stratified according to irrigation status; orange and brown areas in drought damage and crop change maps respectively illustrate overlap across simulations between areas which are rain-fed or newly irrigated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prominence with respect to baseline conditions in all scenarios.

Transformational trends mirror adaptation results, and therefore also hold different implications across scenarios. Results from the RD policy scenarios show more frequent transformations than in baseline conditions, particularly relating to major increases in farm size and input use (Fig. 4a), therefore partly compromising the policy goal to reduce irrigation (SI5). On the other hand, results from the ES policy scenarios show a reduction in transformational adaptations when compared to baseline conditions for all transformational changes except those relating to scale decline and input changes. Under ES policy conditions, these transformational changes result in fewer farmers changing strategy to actively pursue diversification or expansive strategies, and more farmers changing strategy to actively pursue a contractive strategy (SI5).

5. Discussion

5.1. Implications of scenario findings

Our scenario results are largely in line with historical trends (SI5). Ongoing regional processes of agricultural area decline, farm scale enlargement and increased prevalence of permanent crops will continue under all climate change scenarios regardless of behavioral changes by farmers or the implementation of water policies. Both behavior and policy change can however play a significant role in either stimulating or reducing the need for farmers to undertake different transformational adaptations, with important repercussions to farm structure and regional variables. These repercussions are best analyzed by acknowledging the ways in which policy and behavior influence different components of drought vulnerability. MA behavior and RD policy interventions increase the *adaptive capacity* of farms, seeing a smaller and more dynamic future farmer population with higher reliance on (irrigated) permanent crops, diversification activities and expansive strategies. On the other hand, ES water policies solely reduce the *sensitivity* of farms to drought risk, without incentivizing broader transformational change.

Adaptation planning currently focuses on achieving benchmarks of adaptation success, which are often ill-defined. Dilling et al. (2019) have recently proposed that adaptation planning may therefore be better targeted at increasing and measuring the adaptive capacity of individuals and institutions to a broad range of risks. This notion suggests greater potential may be found within initiatives promoting MA behavior and RD policies, where more widespread openness to change and drought risk perception among farmers result in the largest share of engagement in different transformational adaptations. This dynamic highlights the importance of potential linkages between policy and norm formation, requiring an examination of the potential of behavior-focused interventions targeting attitudinal and value change (Gifford et al., 2011). An example of such an intervention is illustrated by the RD policy scenarios, where climate risk communication strongly promotes engagement in adaptation. A more in-depth modelling exploration of the impacts of such informational strategies and other behavior-focused interventions, including penalties or rewards-based approaches (Steg and Vlek, 2009), alongside informal risk communication dynamics (Kandiah et al., 2017) are therefore priority areas for further research. Our modelling results revealed that structural policy interventions (e.g. production regulations and irrigation subsidies) have a more limited influence on increasing a farmer's adaptive capacity in comparison to behavioral approaches. Further research is needed in order to assert whether other structural variables could act as enablers for increased adaptive capacity, for example by further supporting diversifications or collective approaches with the potential to stimulate learning (Bouttes et al., 2019).

By simulating feedbacks between implemented adaptations and farmer assets, goals and irrigation consumption, our model enables the identification of trade-offs, and can therefore inform the adaptation planning process. Notably, MA behavior and RD policy scenarios showed that higher rates of transformational adaptation result in larger and partly more profitable production than under baseline conditions yet see marked declines to the total number of farms. This dynamic is largely reversed under ES policy and LA behavior scenarios. Other trade-offs present potential cases of maladaptation, i.e. situations where implemented adaptations result in increases to vulnerability and vulnerability transfers (Barreteau et al., 2020; Juhola et al., 2016). Trade-offs between agricultural production and water conservation under RD policy scenarios see irrigation quota reductions effectively reduce irrigation withdrawals, but predictably increase drought-risk exposure to irrigated farmers, which, coupled with restricted crop conversions, ultimately results in a decline to regional agricultural revenues when compared to baseline conditions. MA behavior reduces drought exposure because of frequent adaptation and irrigation investments, yet subsequent transitions to high water-demanding crops may be placing these farmers at higher risk of drought damage in the future. The ES policy scenarios also show a potential risk of maladaptation due to declining drought risk perceptions and lower engagement in expansive adaptation despite incentivized irrigation investments, leaving the smallest cultivated area under production and substantial declines to regional agricultural revenues.

Transformational adaptations represent a substantial share of undertaken adaptations in all scenarios. This finding implies substantial social and financial costs will be experienced by farmers, calling for an exploration of the ways in which institutions may compensate for such costs and for a more thorough investigation of potential social limits to adaptation (Adger et al., 2009). Frequent transformational changes in pursued farming strategy resulted in new path dependencies which strongly promoted the continued implementation of expansive practices. This was most evident in the MA behavior scenarios, where transitions to expansionist strategies resulted in greater reductions to drought damage and increases to irrigation than in scenarios where water policies were explicitly designed to target these respective objectives. A unified, integrated drought risk management policy may therefore aim to draw on the benefits of combining initiatives stimulating drought risk perception, and therefore generic adaptation behavior, with targeted irrigation regulations or incentives (Eakin et al., 2014). It must also establish whether and how to prioritize water conservation to avoid the introduction of contrasting measures which both incentivize irrigation expansion (e.g. by increasing drought risk perceptions through awareness campaigns) and reduced consumption (e.g. through subsidized water use efficiency) (Stein et al., 2016).

Trade-offs between socio-economic and environmental sustainability under water and agricultural policy scenarios in Emilia-Romagna were also identified by Bartolini et al. (2007) and Bozzola and Swanson (2014). Similarly, they find that water resource abundance can limit the number of farmers engaging in adaptation and call for a common policy design framework to facilitate the uptake of farm adaptations. Policy recommendations for the more deliberate management of transformational adaptations are furthermore listed by Vermeulen et al. (2018), and include a need to reward farmers for the provision of multiple services, to provide financial compensation mechanisms if necessary transformational adaptations result in significant short-term losses, and to present tools that can monitor and identify trade-offs from the implementation of transformational changes.

5.2. Methodological considerations

Our model distinguishes itself from past work primarily through the representation of farm-level adaptation decision-making as a process embedded within a farmer's wider strategic planning, therefore involving the consideration of both transformational and incremental adaptations. The integration of this perspective within an ABM environment allowed for the quantification of the occurrence and scale of transformational change, as well as the consideration of feedbacks between transformational changes and a farmer's strategic goals. Different conceptualizations of transformational adaptation from the one implemented in our model however exist. According to Kates et al. (2012), transformational adaptations are additionally identified within actions that are entirely new to a region or system, or within actions involving a shift in location. Under these definitions, our modelled adaptations would therefore not be identified as transformational as they primarily illustrate a continuation of historical trends. The absence of such "novel" findings is a direct reflection of both our choice of scenarios and of simulated social processes. We deliberately explored water policy scenarios which reflect presently occurring discourses in the region – yet these discourses largely envisage a continuation of existing policy mechanisms (e.g. expansion of subsidization schemes). For the behavioral scenarios, we focused on exploring the influence of different value and attitude prevalence without simulating potential feedbacks to

broader organizational change. In the absence of deliberately novel and transformational policy (e.g. provision of off-farm employment (Du et al., 2016)), bottom-up collective action (e.g. new farmer associations (Osbahr et al., 2008)), or private initiatives (e.g. relocation of production sites (Marshall et al., 2013)), our results therefore demonstrate future adaptations are likely to be transformative largely only in terms of their magnitude. Further work is needed to operationalize different dimensions of transformational adaptation and shed light on their respective drivers and implications.

The model addressed some of the shortcomings of climate adaptation models identified in the reviews of Brown et al. (2017) and Holman et al. (2018). Unlike many models, we did not assume adaptations as consistent, effective or objective, we captured both triggers and constraints to adaptation, dynamically represented climate, and explicitly represented the decision-making process. The use of ABM further enabled the more fundamental representation of heterogeneous, farm-level characteristics, and therefore adaptation responses (Reidsma et al., 2010; Stringer et al., 2020). We also sought to implement the model at a scale consistent with regional adaptation planning, covering the territorial extent of two local LRIC. Despite the context-specific nature of the model, we characterized the farmer population according to European-wide classifications (production type and farming strategy) and drew on established theories of value and decision-making behavior, therefore presenting opportunities for eventual comparison across European contexts.

Some pitfalls attributed to (agent-based) adaptation modelling and lack of data for parameterization however remain. We used singular, proxy actions to represent two separate diversification strategies; further effort could be placed on improving their representation, for example by simulating adaptive changes within the diversification trajectories themselves as well as processes of withdrawal. Despite integration of social and biophysical processes, oversimplifications were made, and important processes omitted. With regards to biophysical processes, the ABM lacks an important feedback between irrigation expansion and declining irrigation availability, as limits to freshwater resources in the region could not be identified. The integration of this feedback will undoubtedly influence possibilities for irrigation expansion in our model, especially affecting results from the MA behavior scenarios. Additionally, while our model sought to simulate adaptations to water scarcity, interviewed farmers also expressed concern at the increased frequency of cloudburst and hail events. Greater emphasis on multi-hazard responses and the evaluation of mitigation action alongside adaptation should be addressed in future models. Our representation of cumulative soil-wetness disregarded climatic effects throughout the months of November and December and assumed a soil-wetness value of 0 with the beginning of each calendar year, likely resulting in some divergence between our simulated drought projections in comparison to other regional models (Basso et al., 2015). While this representation can provide insight on how farm-level transformational adaptations respond to climate change, more accurate predictions of responses to projected climate change will therefore require the integration of detailed crop growth models. Improved representation of crop and water expansion suitability should also be addressed to increase reliability of results, as the sensitivity analysis revealed the proxy neighborhood radius as particularly influential to modelling outcomes (SI5).

In addition to the need to improve the representation of policy impacts on farmer values and attitudes in further research, similar efforts should be placed on the representation of feedbacks from changing farmer behavior to institutional change. The inclusion of institutions as responsive (rather than external) entities in a land-use change ABM has recently been explored by Holzhauer et al. (2019), who call for empirical analyses of institutional decision-making to facilitate the integration of such processes within socio-ecological modelling. In the context of water management, Valkering et al. (2009) have drawn on literature on socio-technical transitions and used participatory ABM to illustrate how water policy may develop following environmental change, policy-oriented

learning, coalition forming and changing public support and water cultures. Such approaches involve the representation of co-evolving individual and institutional behaviors, and therefore also of decision-making processes of policy-makers, further illustrating how institutions may guide the deliberate implementation of transformational change (Wilson et al., 2020).

6. Conclusions

This study investigated the multi-level processes of transformational adaptation to water scarcity among crop farming systems in Romagna through the development of an empirical agent-based model. Our simulations revealed that scenarios which induce increases to farmer drought risk perceptions have the greatest potential to increase the implementation of (transformational) adaptations and promote expansive adaptations. These trends primarily occur in scenarios simulating drier climates, most-adaptive farming behaviors and water policies aiming at regulating irrigation consumption, and result in a region with fewest reductions in cultivated area, increased irrigation and fewest, highest profit-earning farmers, largely exacerbating presently occurring trends. Policies aiming to ensure irrigation water supply successfully reduce the share of cultivated area witnessing drought-related damages to production, yet by aiming solely to reduce drought sensitivity, they primarily result in declining drought risk perceptions, and therefore see fewer (transformational) adaptations and relatively more farmers implementing contractive adaptations.

Our results reveal the importance of quantifying the occurrence and scope of transformational adaptations in the modelling of farm system adaptations. Transformations represent more than half of annual implemented adaptations on average throughout the simulations, and, in scenarios where more transformations occur, frequently involve farmers changing their goals and adopting an expansionist strategy. This transformation induces new path dependencies, acting as positive re-enforcements which lead farmers to repeatedly engage in expansionist adaptations, with implications for water policy. Policies aiming to regulate irrigation demand promote greater awareness of drought risk, and therefore encourage farmers to purse expansive strategies and invest in new irrigation sources, partly off-setting reductions to irrigation withdrawals promoted by crop regulations and subsidized efficiency investments. Policies aiming to ensure irrigation supply successfully reduce drought damages, and retain a higher number of farmers, yet by disfavoring transformations and promoting contractive adaptations, they result in the most significant declines to agricultural area, and therefore regional revenues. An integrated drought risk management policy may therefore aim to draw on the benefits of either approach, combining a need for increased, generic adaptation capacity with targeted incentives and regulations required for addressing sector-specific goals. As agricultural system models move towards greater representation of farm-level heterogeneity, decision-making, and adaptation processes, we highlight the importance of explicitly accounting for transformational change and see potential in further investigating this concept through further operationalization of its different dimensions, alongside exploration of institutional decision-making and closer representation of value and norm formation.

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.103024.

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