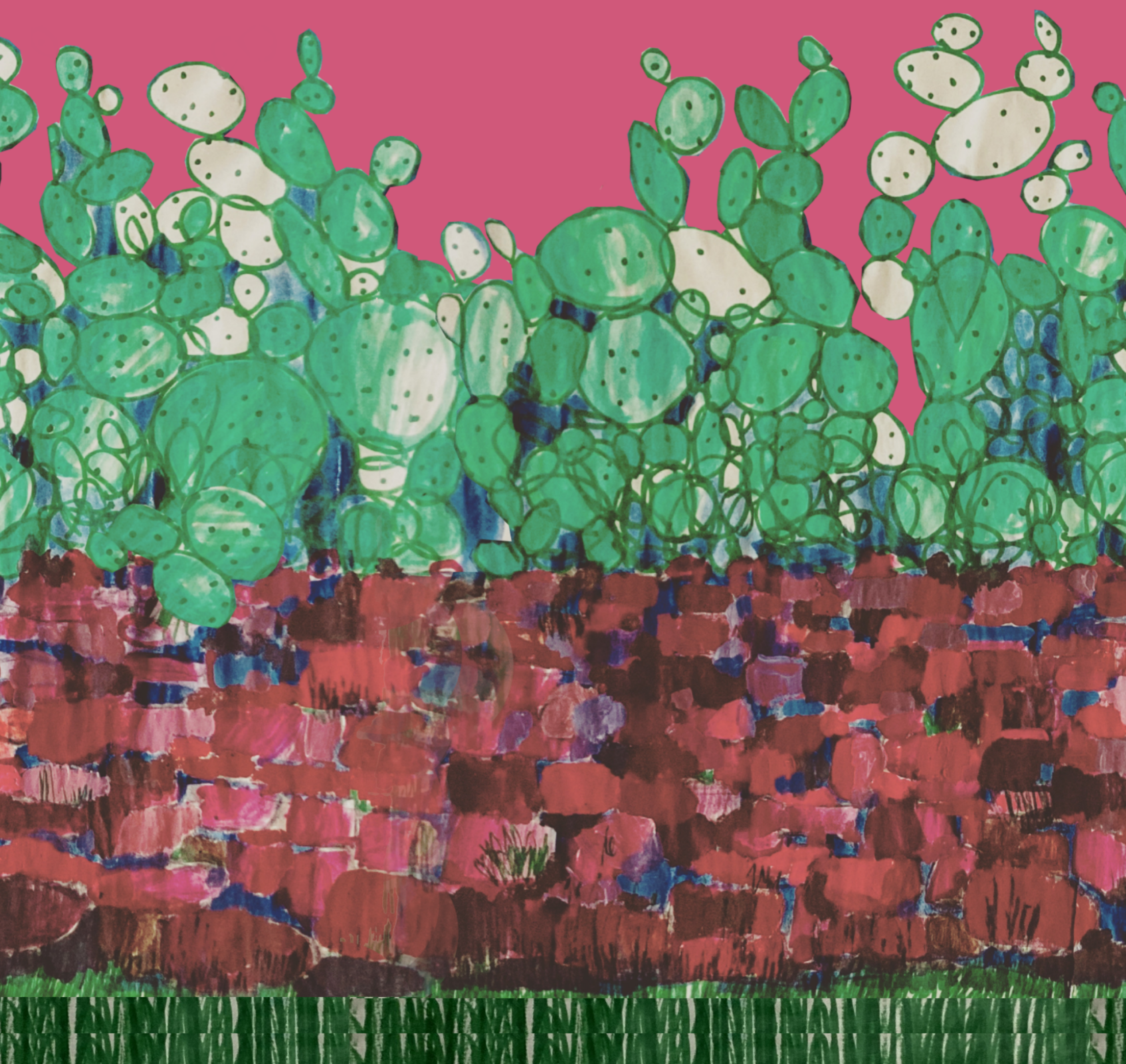
Mapping and modelling adaptation in Mediterranean agricultural landscapes

Zagaria, Cecilia

2022



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Ph.D. thesis, Vrije Universiteit Amsterdam, the Netherlands
ISBN 978-94-6458-765-4

Cecilia Zagaria, Amsterdam, December 2022

Cover design by Benjamin Perrot
Printed by Ridderprint www.ridderprint.nl

This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE). The research in this thesis was carried out at the Environmental Geography Department of the Institute for Environmental Studies, Vrije Universiteit Amsterdam.

VRIJE UNIVERSITEIT

Mapping and modelling adaptation in Mediterranean agricultural landscapes

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor of Philosophy aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. J.J.G. Geurts,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Bètawetenschappen
op maandag 12 december 2022 om 11.45 uur
in een bijeenkomst van de universiteit,
De Boelelaan 1105

door

Cecilia Zagaria

geboren te Rome, Italië

promotoren: prof.dr.ir. P.H. Verburg
dr.ir. C.J.E. Schulp

promotiecommissie: prof.dr. W.J.W. Botzen
prof.dr. F. Kienast
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“If you know one landscape well,

you will look at all other landscapes differently.

And if you learn to love one place,

sometimes you can also learn to love another.”

– Anne Michaels, *Fugitive Pieces*

Summary

Remnants of agricultural landscape features dating back hundreds and even thousands of years can be seen all throughout the Mediterranean Basin, be it in the manually crafted dry stonewalls and terraces delineating fields, or in the historical olive presses and mills which oftentimes populate them. Despite their long-standing occurrence, these landscape elements have persisted in a region which has borne extreme dynamism and change. In fact, these features themselves are the products of adaptation processes, as Mediterranean farming communities have long sought to mold an otherwise difficult land and preserve its scarce resources.

Over the past half century, agricultural landscapes of the Mediterranean region have continued to transform. From a land system perspective, these changes can be categorized as belonging to one of two contrasting trajectories. Throughout marginal areas of Mediterranean Europe, agricultural landscapes have been prone to gradual abandonment processes; elsewhere, transitions toward high-intensity farming and specialization have more often prevailed. Despite the opportunities both changes may bring, there is evidence of negative social and environmental impacts emerging as a result of ensuing landscape homogenization, and thus reduced multifunctionality. While abandonment has been associated with a loss of cultural heritage, the silting of water channels, and reduction of species adapted to semi-natural environments, greater intensification has exacerbated land degradation, freshwater overexploitation, excessive fertilizer consumption, and biodiversity loss. These negative consequences bear more weight given the current planetary crisis and the Mediterranean's positioning as both a biodiversity and climate change "hotspot".

Unravelling the drivers and causal pathways behind these landscape transitions is crucial for the development of effective interventions aiming to minimize the likelihood of adverse outcomes. Studies have found that both abandonment and intensification in the Mediterranean region however share several driving forces, revealing the pivotal (yet underexplored) role and agency of farmers in shaping the landscape. Investigating such farm-level decision processes requires the characterization of human and environmental components of the farm, as well as an exploration of multi-level drivers and feedbacks which may give rise to non-linear dynamics. These features are known to characterize so-called "complex social-ecological systems", and we can therefore make use of specific methodological considerations for their analysis. Notably, these include relying on the integration of empirical observations with dynamic models and scenarios capable of capturing feedbacks, adaptive processes, and uncertainty.

This thesis draws on these methodological principles to explore possible futures for Mediterranean agricultural landscapes, investigating where and how farm-level adaptations may occur under changing conditions. It is structured around two sub-national case studies and a continental-scale analysis capturing different landscape change realities affecting the region. This work begins with an empirical characterization, in **Chapter 2**, of the farm-level drivers, actors, and feedbacks shaping adaptations in the olive landscape of Gera (Lesvos, Greece), a mountainous rural municipality which has been experiencing abandonment and depopulation. This chapter constructs a farmer typology based on extensive semi-structured interviews with farmers. It finds that despite holding different characteristics, both "active part-timers" and "disengaged" farmers are contributing to gradual abandonment processes primarily through constrained ability to farm, regardless of a potential willingness to continue doing so. A third "professional" farmer type is currently both able and willing to invest and intensify their farming system and is supported by socially oriented cooperatives which both promote cultural farming motives and valorize the local, traditional produce. These results are combined to those of a landscape preference survey undertaken with tourists on Lesvos, finding these landscape users to favor cultivated landscapes and elements of traditionality within built infrastructure. Tourist perspectives may therefore synergize with farmers and social cooperative initiatives which view land as valued heritage and see potential for aligning such values with (agri-)tourism development. Whether these opportunities are enough to maintain the cultivated olive landscape is however uncertain. Limited alternative employment opportunities are keeping some (reluctant)

farmers in the sector, yet declining agricultural profits, limited subsidy opportunities for part-time farmers, and low prevalence of willing successors suggest abandonment may well continue in the future.

Chapter 3 takes two of the key driving forces of landscape change identified in Gera, notably sectoral profitability and presence of social cooperatives, and develops a spatial agent-based model precisely to explore which landscapes these drivers may promote or hinder in the future given the farm and farmer characteristics and decision-making behaviors revealed by the interviews. The model reveals that both increased profitability and social cooperatives are required to reverse abandonment trends within the forthcoming 25 years, as each driver promotes a different pathway toward (re)cultivation of the landscape. Social cooperatives exert their influence by maintaining or promoting a cultural drive among farmers, increasing generational renewal, full-time professionalism, and opportunities for intensification. However, a concurrent increase in olive oil prices and subsidy support is found to be necessary to boost transitions away from the "detached" farmer type, and thus halt the abandonment of marginal fields. This latter finding calls for greater reflection on policy instruments, such as subsidies, as well as on the structure of social cooperatives to secure sufficient income to farmers and allow for investment and entrepreneurship. The model presented in this chapter was developed iteratively in consultation with the local farming community and experts in landscape change research. By presenting the model as on object open to critique in all its constituting aspects and emphasizing its explorative nature, this participatory process was crucial for increasing the model's credibility and showed potential as a tool for facilitating discussion on the complexities inherent to landscape change processes.

Chapter 4 similarly made use of an empirical agent-based model to explore how dynamic external drivers and farmer behaviors may drive future landscape change across a second Mediterranean case study – the historical region of Romagna (Italy). Romagna represents a more competitive agricultural reality than Gera, where farm transitions are directed at scale enlargement and crop specialization, as opposed to abandonment. It is additionally one of the most important regions, nationally, with regards to the adoption of on-farm income diversification pathways, ranging from engagement in non-agricultural activities to the development of shortened supply chains. The agricultural landscape is also more diverse and is comprised of permanent, as well as horticultural and cereal crops. Romagna is however drought prone due to low precipitation rates and streamflow from the Apennines, and this chapter therefore primarily explores how landscape changes may ensue from the water policies and farmer behaviors which are evolving in relation to this problematic of relevance to the broader Mediterranean region. The agent-based model, characterized based on the integration of interview findings, secondary sources, and behavioral theory, finds that policies promoting greater drought risk awareness, alongside a prevalence of experimental attitudes among farmers, are resulting in greater dynamism and prevalence of expansionist strategies, leaving a large area under cultivation of fewer, consolidated farms producing high-revenue irrigated crops. While such policies run the risk of offsetting water reduction goals by promoting generic adaptation behavior and thus also investments in irrigation, measures strictly regulating water demand may on the other hand prove unattractive as they limit transitions toward higher revenue productions. Conversely, policies solely aiming to increase water availability to farmers will reduce their sensitivity to drought yet fail to incentivize broader engagement in adaptation. Ultimately, these similarly result in a smaller and less profitable agricultural landscape. An integrated drought risk management policy may therefore consider the trade-offs of different approaches and evaluate a need to reduce drought damages to farmers while also considering the benefits of promoting broader adaptation capacity.

Both Chapter 3 and Chapter 4 outline the relation between specific adaptation decisions and a farmer's wider strategic planning and explore the possibility of farmers switching their strategies and thus preferences for adaptive action following the evaluation of new options which align with their values and needs. This feedback is currently underexplored within agent-based models of social-ecological systems yet is critical to understanding the potential consequences of policy actions, as new strategies enact new path-dependencies which may result in unforeseen outcomes. In both chapters, these feedbacks are referred to as examples of "transformational adaptation", alongside adaptations requiring a greater magnitude of change when responding to particularly severe impacts.

In **Chapter 5**, the focus shifts from exploring *how*, i.e., through which pathways, incremental or transformational adaptations are enacted, to exploring *where* these may be implemented by identifying and mapping proxies of biophysical and socio-economic pre-conditions to change across the Mediterranean region. This work investigated the current suitability of a range of sustainable farm-level adaptations to increased drought and heat stress. Incremental adaptations addressing a farm's soil, crop, and water sub-system where respectively represented by the implementation of reduced tillage, crop variety change, and drip irrigation, while transformational adaptations were represented by conservation agriculture, crop change, and irrigation expansion. Importantly, this analysis found transformational adaptations to have a lower potential for implementation, especially within areas where the most adverse changes to drought and heat stress are forecast to occur under climate change – notably across the south-western and eastern rims of the Mediterranean Basin. Within these areas, the most tangible potentials are found for crop changes and reduced tillage, while the fewest opportunities are identified for irrigation expansion and variety change. Socio-economic factors, such as distribution of irrigated crops, land ownership, market access, and poverty, were furthermore identified as the most significant factors limiting the implementation of adaptations within high impact areas. In areas where a greater discrepancy has been found between adaptation need and adaptation potential, action may therefore be placed on securing more favorable conditions across these four factors, as well as on evaluating the potentials and costs of more transformational options.

Chapter 6 provides a synthesis of this thesis' research findings, presenting a comprehensive characterization of the identified farmer types, their relations to influential drivers of change, and the ensuing adaptation pathways which

may shape the broader Mediterranean landscape. This characterization emphasizes an existing diversity of farmer decision-making processes determined by heterogeneous abilities, needs, attitudes, and values. This diversity holds implications for agricultural policy which has often upheld an intensification and modernization paradigm while overlooking diversified, smallholder realities and cross-sectoral policy coherence. Processes of local participation and experimentation can thus be invaluable in the design of more targeted and needs-based policy instruments. Coupling these insights with a dynamic analysis of their respective social-ecological impacts can further contribute to anticipating maladaptive outcomes and vulnerability transfers – and may therefore help shape a fairer and more resilient future for the Mediterranean region.

Chapter 1

Introduction

Chapter 1 – Introduction

1.1. Background

The term "Anthropocene" was first introduced by Crutzen and Stoermer (2000) over twenty years ago to suggest the advent of a new geological epoch, one that explicitly recognizes human societies as dominant forces shaping the earth's biogeochemical cycles and ecosystems (Steffen et al., 2011). While the formal establishment of the Anthropocene Epoch remains contested (Lewis & Maslin, 2015; Steffen et al., 2011), the scale, rate, intensity, and diversity with which humans are affecting the global environment, from altering its atmospheric composition to driving non-human species decline, is unequivocally unprecedented (Ellis, 2015). Scientific estimates are suggesting that several "safe" planetary boundaries may already have been breached by human activity (Lade et al., 2020), potentially contributing to the de-stabilization of the planet towards a new and undoubtedly societally disruptive state (Steffen et al., 2018). Attaining a safe, just, and sustainable planetary future (Vince, 2012) will require not just a quantification of (adverse) human impacts on environmental systems, but foremost a greater exploration into the causal mechanisms delineating possible pathways of societal change (Ellis, 2015).

The ambition to understand the causal linkages coupling human and environmental systems, and to predict the outcomes of these interactions, is at the heart of numerous interdisciplinary theories and frameworks (Ellis, 2015), including the social-ecological systems (SES) framework (Berkes et al., 1998). At the time of its inception in 1998 (Berkes et al., 1998), the SES framework was designed to analyze the potential for resilience in local resource management problems. At its core, it illustrated ecological and social systems as individually nested but coupled systems, and identified the ecological knowledge of resource users as a primary linkage between the two structures (Colding & Barthel, 2019). Several different definitions have since been ascribed to SESs, in some cases providing the basis for the emergence of novel theories and frameworks (Colding & Barthel, 2019). Two of these developments, notably the Coupled Human and Natural Systems framework (Liu et al., 2007), and the interpretation of SESs as Complex Adaptive Systems (Levin et al., 2013; Preiser et al., 2018), build on SES theory to additionally characterize its complexity. This approach is most explicit under a Complex

Adaptive Systems perspective, where complexity is largely framed as a consequence of the adaptive capacities of SESs, and their respective feedbacks (Preiser et al., 2018).

From a planetary boundaries perspective, agricultural landscapes represent a critical SES whose management is significantly contributing to planetary health decline (Campbell et al., 2017; Rockström et al., 2009). This is evident in the greenhouse gas emissions attributed to agricultural land dynamics, as well as their specific role in driving deforestation, excessive freshwater withdrawals, biodiversity decline, and nitrogen and phosphorus cycle disruptions (Campbell et al., 2017). The present-day encroachment on the planetary boundaries can partly be attributed to a lack of engagement with the complex properties of agricultural landscapes. Motivated by productivist goals, their management has often favored the pursuit of so-called silver-bullet, or "tame" solutions (i.e., restricted solutions reliant on a fixed technical or institutional change), and has therefore largely disregarded feedbacks and non-linear dynamics (DeFries & Nagendra, 2017; Meyfroidt et al., 2022). The inadequacy of these approaches is appropriately exemplified in the so-called "irrigation efficiency paradox" (Grafton et al., 2018) which emerged from observations that increased irrigation system efficiency, deployed as a strategy to reduce agricultural water consumption, could instead induce farmers to recover and reuse their water savings, for example by expanding irrigated areas or switching to more water intensive crops. In an increasingly globalized and tele-connected world, these social feedbacks are importantly expanding their basin of influence to more distant spaces and time scales, increasing the possibility of unforeseen spillover effects, and thus of undermined policy objectives (Meyfroidt et al., 2022).

Alongside more efficient irrigation systems, a range of agronomic practices and management strategies have been put forward as potential solutions to both reduce pressure on ecological systems and simultaneously adapt to increasingly adverse ecological conditions brought about as a result of climate change (Bennett et al., 2016; Klerkx et al., 2019; Scherer & Verburg, 2017). The challenge therefore lies not in their identification, but rather in the exploration of where and how they may successfully be implemented without inducing unforeseen outcomes and vulnerability transfers (Barreteau et al., 2020; Prestele & Verburg, 2020). Such an investigation firstly requires an exploration of human behavioral responses to changing drivers and feedbacks. Secondly, it involves the delineation of adaptation pathways which can successfully deliver on the strategies' intended goals. By engaging with principles of SES complexity and adopting a mixed-method and multi-scalar approach, this thesis broadly aims to address these two core knowledge gaps. This exploration is undertaken for the Mediterranean Basin, a highly dynamic and heterogeneous region where increasingly adverse climatic impacts and shifting socio-economic realities are progressively restricting the multifunctional potential of its agricultural landscapes (Cramer et al., 2018; Debolini et al., 2018).

1.2. The Mediterranean Basin as a case study for exploring agricultural adaptation

1.2.1. Heterogeneous agricultural landscapes of the Mediterranean Basin

The Mediterranean Basin is characterized by a high diversity of agricultural landscapes adapted to the region's harsh bio-climatic conditions (Malek & Verburg, 2017). The presence of the Mediterranean Sea, the distribution of the region's mountain ranges, and prevailing winds all contribute to the Mediterranean's unique climate, defined by a particularly warm and dry summer season and a mild winter during which most annual precipitation occurs. The region is largely considered resource-scarce in terms of both water and soil resources. Months of summer aridity in combination with a largely mountainous and sloping terrain have resulted in the prevalence of poor soils, with limited, higher fertility in coastal areas and alluvial plains (Perez, 1990).

The diversity of agricultural production occurring across the Mediterranean Basin in part mirrors the presence of these geographical constraints. Open grazing (e.g., in rangelands) is primarily practiced across North Africa and the Middle East in areas of lower precipitation and higher altitude (Malek & Verburg, 2017), where shrubs and annual vegetation adapted to heat, drought, and salinity are present to enable grazing (EL-Barasi et al., 2013).

Irrigated croplands producing major Mediterranean crops including cotton, vegetables, citrus and other fruit, cover 14% of all land and are concentrated along the region's major rivers and in areas enabled by water transfer or treatment infrastructure (Daccache et al., 2014; Fader et al., 2016; Malek & Verburg, 2017). Rain-fed cropping systems based on the production of cereals (primarily wheat and barley) and drought-adapted permanent productions (e.g., olive and grape) (Portmann et al., 2010) are on the other hand widespread throughout the Mediterranean and found particularly within areas of lower rural population density, as are its characteristic mixed-use mosaics. The latter include the noted *montado* or *dehesa* systems of Portugal and Spain which involve the mutually beneficial and integrated undertaking of woodland, pastoral, and cropland based activities (Malek & Verburg, 2017; Rodriguez-Rigueiro et al., 2021).

Different farming systems manage these productions and shape the broader agricultural landscape. In comparison to other farming regions (including Northern Europe), the Mediterranean Basin holds a greater portion of smallholder farms and fragmented land holdings (Caraveli, 2000; Napoléone & Melot, 2021). Smallholder farms are characterized by lower use of external inputs (including hired labor), with both full-time and part-time households keeping a significant share of produce for self-consumption. Part-time farming is especially prevalent throughout the region and reflects a plurality of objectives, ranging from a lifestyle "hobby" choice to a livelihood diversification strategy sustaining household income through precarious times. Despite these widespread realities suggesting a lower degree of market integration, the regional agricultural sector is also home to a (growing) export-oriented market comprised both of smallholders (in the case of niche markets, e.g., mint production in Morocco) as well as larger, more intensive agri-businesses specializing in high-value productions (e.g., tied to permanent crops) (Guarín et al., 2020; Marzin et al., 2017).

Each of these farming systems, according to different perspectives, contributes to the creation of a "traditional", "multifunctional", or "cultural" landscape, resulting in these terms being commonly found as descriptors for

Mediterranean agricultural landscapes (Muñoz-Rojas et al., 2019; Teresa Pinto-Correia & Vos, 2004). Traditional smallholder systems in particular have been praised for supporting the region's valued socio-cultural heritage, be it through the maintenance of mosaic land systems, historical productions, or centuries-old cultivated terraces (García-Ruiz et al., 2020). Such systems are similarly valued for their contributions to biodiversity (Quintas-Soriano et al., 2022). This is highly relevant as the Mediterranean Basin is considered one of 34 global biodiversity hotspots (Debolini et al., 2018) and is characterized by high species endemism (García-Vega & Newbold, 2020). In addition to traditional farming systems, more "modern" farms have also been found to play a role in constructing regional (cultural) multifunctional landscapes, for example by sustaining tourism infrastructure (e.g., through agri-tourism), or by engaging in value-chains certifying the Geographic Indication of regional produce (García-Martín et al., 2021; Moragues-Faus et al., 2013).

1.2.2.Recent drivers of agricultural landscape change

Mediterranean agricultural landscapes therefore embody elements of persistence as well as transformation. From a land change perspective, recent agricultural change trajectories have primarily been defined by intensification, expansion, and abandonment processes (Debolini et al., 2018; Jiménez-Olivencia et al., 2021). While abandonment has dominated transitions across Mediterranean Europe, changes across North African and Middle Eastern landscapes have witnessed greater expansion and stability (Levers et al., 2018; Winkler et al., 2021). Evidence has demonstrated that each trajectory may both be supported, or inhibited, by the same underlying driving force, depending on the objectives and abilities of the farmers responding to change. This observation has been noted, among others, in two recently published reviews aiming to present a synthesis of contemporary driving forces of land use change across the Mediterranean Basin, notably by Debolini et al. (2018) and Jiménez-Olivencia et al. (2021).

According to their findings, declining profitability of agricultural production has strongly driven each of the three dominant trajectories. The regional importance of the "cost-price squeeze" has similarly been discussed by Moragues-Faus, Ortiz-Miranda and Marsden (2013). Echoing Marsden (2003), they describe the three primary modes of farming exemplifying the archetypal adaptations to declining profitability in the region, each delineating potential causal pathways to the identified landscape changes. In a first "agro-industrial" model, changing market prices and increased costs of production have induced some farmers to expand, specialize, and intensify their productions to increase yields and thus profit margins. In the second "post-productivist" model, intensification and expansion are pursued yet tamed by agro-environmental farming objectives. In the final "new rural development" model, farmers are pushed to explore alternative multifunctional pathways, either by shortening supply chains, or by developing on- and off-farm income diversification strategies often associated with the (partial) abandonment or extensification of agricultural land.

These varying responses to falling agrarian income are emblematic of dynamics which have occurred in other parts of the world, including elsewhere in Europe, mirroring the widespread focus agricultural policy has placed on modernization, and thus on contributing to increased costs of production (Marzin et al., 2017; van der Ploeg & Roep, 2003). In comparison to European-wide dynamics, however (van Vliet et al., 2015), demographic drivers have held a more prominent role in the Mediterranean Basin. These have affected both mountainous, marginal areas, where rural exodus has contributed to a lack of successorship and increased abandonment, as well as peri-urban regions, where increased urbanization (largely driven by coastal tourism) has replaced cropland cultivation. Another unique dimension of the region thus lies in its reliance on an older generation of farmers, and so also on non-agricultural forms of welfare (i.e., pensions) to sustain farming systems which would otherwise struggle to remain active (Marzin et al., 2017; Moragues-Faus et al., 2013). Of additional importance for all regional dynamics have been changing infrastructural and technical aspects (e.g., increased access to markets or irrigation (Debolini et al., 2018; Jiménez-Olivencia et al., 2021; Muñoz-Rojas et al., 2019)), alongside political changes (e.g., agricultural policy reforms, land privatization, trade liberalization, and political instability (Duarte et al., 2021; Harmanny & Malek, 2019)).

1.2.3. Adverse consequences of agricultural landscape change and outlook

These landscape transitions, primarily ongoing since the 1950s (Duarte et al., 2021; Jiménez-Olivencia et al., 2021), have brought about some negative consequences, in most cases as a result of reduced multifunctionality following a polarization of the landscape toward either high-intensity, specialized farmlands or abandoned agricultural fields (Marzin et al., 2017). Following abandonment, a loss of heritage has been associated with lost traditional practices and features (in the case of collapsing terraces, additionally contributing to the silting of water channels), as well as a reduction in species adapted to semi-natural agricultural landscapes (Jiménez-Olivencia et al., 2021). Concurrently, intensification (and expansion of intensively managed cropland) in other areas has also led to a homogenization and simplification of the landscape, while further increasing the risk of land degradation, freshwater overexploitation, disruption of biodiversity and habitat ecosystems, and excessive fertilizer consumption (Caraveli, 2000; Malek et al., 2018; Nainggolan et al., 2012).

Whether the future holds a continuation of "business-as-usual" with regards to regional agricultural landscape change is of course uncertain. The Mediterranean Basin has been identified as a climate change "hotspot", and we can therefore expect the regional agricultural sector to increasingly be confronted with production risks following increases in the occurrence and intensity of extreme events, especially heat stress and drought (Cramer et al., 2018). Current possibilities to intensify productions, particularly in the south and eastern Mediterranean where yield gaps are more substantial (Mueller et al., 2012), are therefore likely to become water-limited in the very near future (Cramer et al., 2018). Yet regional population is expected to continue growing and to further induce urban expansion (Malek et al., 2018). Sustainable intensification approaches may therefore be required to ensure regional food security (particularly in the southern Mediterranean, currently heavily reliant on imports (Malek et al., 2018)) while guaranteeing the protection of regional environmental resources, livelihoods, and biodiversity.

A recognition of the need for new, holistic, policy is starting to emerge and additionally place emphasis on the promotion of sustainable initiatives. Such integrated perspectives can be identified in policies promoting multifunctionality, ranging from the field scale (e.g., through agro-ecological practices), to the farm and landscape scales (e.g., through on-farm diversification or rural development initiatives incentivizing generational renewal and pluri-activity, thereby addressing dynamics pertinent to historically more marginalized communities) (Fayet et al., 2022; Marzin et al., 2017). Embedded in some of these initiatives are specific elements further challenging past intensification paradigms, for example in policy perspectives striving to reduce unsustainable demands on fertilizer use, as envisaged by the European Union's "Farm to Fork" strategy (Schebesta & Candel, 2020), or water consumption (Commission, 2012; Iglesias, Garrote, et al., 2011; Sowers et al., 2011). The implementation and success of such initiatives has however thus far been limited, and policy coherence remains a challenge (Marzin et al., 2017; Scown et al., 2020).

1.3. Approaches to mapping and modelling agricultural adaptation: bridging farm and landscape scales

1.3.1. The actor-land change conceptual model

Past analysis of Mediterranean landscape change (**section 1.2.2**) has identified the farm scale as a fundamental unit of analysis for unravelling the causal mechanisms and feedbacks determining landscape-level configurations. It enables the identification of how a unique driver, as is the case with reduced agricultural profitability, may induce vastly different, if not opposed, trajectories of change. According to the conceptual categorization of Hersperger et al. (2010), such methodological explorations would fall under the "actor-land change" conceptual model. While other (more commonly implemented) conceptual models in land change research directly correlate drivers to land changes, or assume a linear relationship between drivers, actors, and change, the actor-land change model explicitly investigates the decision-making processes of individual actors, and the cumulative effect of their actions on the landscape. The emphasis on decision-making importantly addresses the representation of causal pathways and considers behavioral feedback mechanisms, including learning and adaptation. The decision to engage with properties of SES complexity influences the choice of conceptual model, and thus of research questions and methodologies. On the one hand, understanding complexity requires the integration of complementary research approaches (Preiser et al., 2018). On the other, it places specific value on the exploration of the actor-centered model.

1.3.2.Methodological considerations of engaging with SES complexity

Engaging with SES complexity brings forward additional, and specific, methodological considerations. While no unified definition of complexity in SES research has been put forward, Preiser et al. (2018) propose a typology of six organizing principles outlining the features and attributes of SES as complex adaptive systems. For each of these, we can characterize the primary ways in which they apply to the dynamics governing agricultural landscape change across the Mediterranean Basin (**Table 1.1**). Three core methodological insights can be drawn from this description (Preiser et al., 2018). The first relates to complexity being "contextually determined", and thus benefitting from empirical explorations primarily by means of case studies and participatory approaches which can shed insight onto actor-specific characteristics and decision-making. Secondly, complexity features are to a large degree a function of multi-scalar feedbacks and dynamic and adaptive processes. Dynamic (spatial) models are therefore especially useful tools which may draw on causal insights derived from empirical observations and re-construct relational dynamics to identify possible pathways and outcomes of change. Lastly, scenario development may complement such dynamic models to navigate the high degree of uncertainty characterizing complex SES under change.

Table 1.1 – Organizing principles of complex SES (Preiser et al., 2018) and examples of relevance for Mediterranean agricultural landscapes.

Organizing principles of complex SES	Examples of complexity demonstrated by Mediterranean agricultural landscapes
Relational	Agricultural landscapes are constructed by both landscape "makers" (e.g., farmers) and "users" (e.g., tourists) (Pinto-Correia & Kristensen, 2013) – they are a product of interaction, as much as of components (Preiser et al., 2018). These interactions primarily relate to a relationship between people and land (e.g., arising from crop cultivation or ascribed cultural meanings). However, further "nested"

	relational components exist both within and across social and environmental systems (e.g., socially, Mediterranean agricultural landscapes are nested in global food systems and regional rural development (García-Martín et al., 2021), while environmentally they are nested within global bio-geochemical cycles (Aguilera et al., 2021)).
Adaptive	Mediterranean agricultural landscapes have evolved over a long of history of interaction and co-adaptation between people and nature (Ruiz & Sanz-Sánchez, 2020). The crops characterizing the region, as well as the more complex land management strategies, are demonstrative of evolutionary processes and social learning (e.g., terracing in arid environments (Meister et al., 2017)). Importantly, adaptations may furthermore be anticipatory, instead of reactive, especially in consideration of climatic change (Eitzinger et al., 2010).
Dynamic	Multiple trajectories of change are characterizing Mediterranean agricultural landscapes. These different trajectories may emerge from the same underlying driving force, yet be molded by different farm-level characteristics, (stochastic) processes, and feedbacks, resulting in non-linearity and high unpredictability (Debolini et al., 2018).
Radically open	The features and processes shaping Mediterranean agricultural landscapes are constantly subject to change from external factors, making the "boundaries" of this system highly porous and difficult to define. Recent examples include increasing spatial teleconnections (e.g., responses to global food demands), novel actors and farming motivations (e.g., farm labor flows and large-scale private investors), and climatic risks (Cramer et al., 2018; Duarte et al., 2021; García-Martín et al., 2021; King et al., 2021; Napoléone & Melot, 2021).
Contextually determined	Despite displaying unique common features, Mediterranean agricultural landscapes are highly diverse and reflect multiple context-dependent realities (Malek & Verburg, 2017), including (historical) institutional arrangements, biophysical constraints, food demands, and farmer characteristics and motivations (Pinto-Correia et al., 2014).
Displaying emergent properties from complex causality	The same underlying drivers of change (e.g., declining profitability of the agricultural sector, rural depopulation) have been leading to different adaptation pathways within Mediterranean farming systems in part due to their different characteristics and respective feedbacks. These adaptation pathways are in turn manifested in different landscape change trajectories (e.g., agricultural abandonment, intensification, or expansion) (**section 1.2.2**) (Debolini et al., 2018).

1.3.3.Agent-based modelling as a tool for engaging with SES complexity

Agent-based modelling (ABM) is a methodological approach which stems from complexity science and has often been deployed precisely to allow for a better representation of SES dynamics to identify the potential outcomes of scenario conditions. In this context, ABMs involve the explicit representation of the decision-making processes of heterogeneous actors (which may range from individuals to institutions or collectives), as well as the interactions between actors and their external social and ecological environments. They are therefore key examples of the implementation of an actor-land change conceptual model. ABMs have increasingly been applied to generate dynamic and spatially explicit insight in land system change research (Matthews et al., 2007), where interactions may bridge multiple spatial as well as temporal scales.

Though ABMs were originally most often parameterized with artificial data to scope theoretical questions, they are increasingly empirically-based and constructed through (mixed-method) participatory means (An, 2012; Valbuena et al., 2008). This latter approach has relied on (iterative) stakeholder consultation to characterize the model, i.e., define its primary components, notably the influential social and ecological external environment, the characteristics of actors (including their goals, values, and assets), their enacted adaptations, and the decision-making trajectories and feedbacks linking changes in the external environment to actor adaptations (Schlüter et al., 2017). In such a participatory context, ABMs are increasingly used toward policy design and evaluation, as the differentiation of different farmer behaviors helps investigate which policy mechanisms may work under which internal as well as external conditions (e.g. Tieskens, Shaw, et al. (2017)). In a European agricultural context, ABMs have contributed to developing these necessary farmer behavioral typologies to investigate adaptations related to agro-environmental policy engagement, structural farm changes, and their impacts on the production of ecological externalities (Huber et al., 2018). Despite these advancements, there is potential to further enhance the representation of behavioral complexity in such models in order to meaningfully strengthen their policy relevance (Huber et al., 2018). Literature has drawn specific emphasis on the need to improve the integration and representation of farmer values and learning processes, as well as key dynamics of regional farming systems, notably their engagement with on- and off-farm income diversification and climate adaptation processes (Holman et al., 2018; Huber et al., 2018).

1.4. This thesis

1.4.1. Research questions

The overarching aim of this thesis is to draw on the methodological and organizational principles of SES complexity to explore possible futures for Mediterranean agricultural landscapes by investigating where and how adaptations can successfully be implemented. Agricultural landscape change is hereby conceptualized as the aggregate outcome of adaptation decisions taking place at the farm scale. Farms and farmers therefore represent the primary agricultural unit of analysis of this thesis. This thesis furthermore specifically focuses on cropland dynamics only, excluding livestock or mixed cropland-livestock farming systems, as these can display vastly different properties and adaptation possibilities (Aguilera et al., 2020).

More specifically, this thesis scopes (1) which farm-level drivers, actors, and feedbacks are shaping adaptations in Mediterranean agricultural landscapes, and (2) which implementation pathways can successfully deliver on the adaptation's intended goals. The definition of adaptation used in this thesis primarily refers to all farm-level changes implemented by farmers in response to an (anticipated) stressor with the aim of reducing a farm's vulnerability, thereby expanding on common definitions of adaptation (Schipper, 2007) which refer specifically to climate change responses. The notion of "successful" adaptation is thus also generally reflective of a farmer's perspective, yet by investigating farm-level adaptation manifestations across the wider agricultural landscape, this approach can inform more plural reflections on adaptation "success".

The following questions were formulated to guide the research. Each research question addresses one or more elements of the driver-actor-change framework (Hersperger et al., 2010) (**Figure 1.1**), thereby presenting a comprehensive investigation of agricultural land change processes:

RQ1a – Which farm-scale drivers, actors, and feedbacks are shaping adaptations in Mediterranean agricultural landscapes?

RQ1b – How may these elements be characterized to enable a spatial forecasting assessment for different adaptations across the region?

RQ2a – Which implementation pathways can successfully deliver on the adaptation's intended goals?

RQ2b – What can we learn from spatial scenario explorations of farm adaptations across Mediterranean landscapes, and how may these insights inform research and practice?

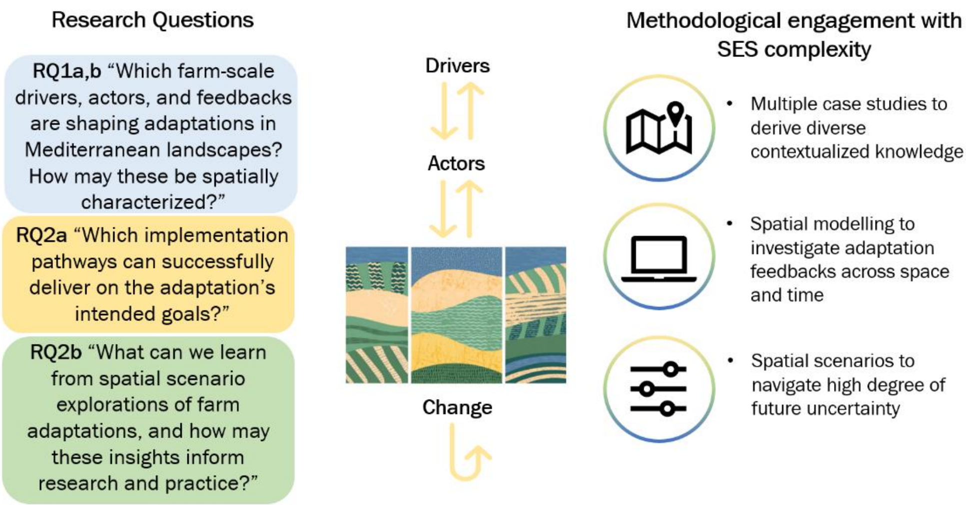

Figure 1.1 – Investigated research questions and methodological engagement with SES complexity. Landscape illustration is credited to: iStock.com/MariaPetrishina.

1.4.2. Thesis structure

This thesis is based on two sub-national case studies and a continental-scale analysis capturing different landscape change realities affecting the Mediterranean Basin. Chapters 2 and 3 are situated in the municipality of Gera, in the eastern coast of Lesvos Island (Greece). The municipality is emblematic of regions characterized by declining agricultural profitability and extensive production systems, where transitions to part-time and pluri-active farming are gradually representing the prevailing forms of adaptation and are contributing to land abandonment processes. The primary drivers investigated in Gera are the role of "bottom-up" landscape initiatives, striving to valorize produce and capitalize on the rich cultural heritage of the region to maintain the olive plantations, alongside changes to sectorial profitability. Chapter 4 is instead situated in the historical region of Romagna (Italy) and addresses commercial, full-time, farming systems adapting to declining profits and climate change by engaging in different multifunctional pathways, for example by expanding the range of non-agricultural farm-based activities, or by valorizing produce through shortened supply chains. In this context, different water policy perspectives are furthermore explored as an external driver of change, scoping how their often-overlooked influence on strategic decision-making affects regional water consumption. The final Chapter (5) instead focusses solely on land and water management-based adaptations that can reduce yield vulnerability under climate change, thus presenting a more productivist farming perspective.

All chapters address the first two research questions (RQ1a and RQ1b), and thus involve the (spatial) characterization of drivers, actors, feedbacks, and farm-based adaptations. While Chapters 2 to 4 primarily base this characterization on semi-structured interviews, Chapter 5 solely relies on secondary spatial data and literature to characterize the system components. The central chapters (Chapters 3 and 4) address all four research questions but primarily make use of spatial agent-based modelling in response to RQ2a, and therefore are examples of more comprehensive, dynamic explorations of how agricultural landscape change occurs. Both agent-based models are constructed by implementing mixed-method approaches, building on insight derived from partly qualitative field interviews as well as from the analysis of socio-economic (spatial) trends. The degree of complexity is greater in Chapter 4 than in Chapter 3, as additional adaptation feedbacks are explored in relation to climate change, behavioral, and institutional policy scenarios. The final research question (RQ2b) is addressed by Chapters 3 to 5 and thus integrates contributions from each of the different adaptation trajectories explored in both case studies as well as through the continental spatial analysis.

Chapter 6 is the concluding chapter and returns to the stipulated research questions to reflect on the contributions and advancements brought forward by this research. **Figure 1.2** summarizes the structure of this thesis, illustrating which chapters address which research question, and through which principal methods.

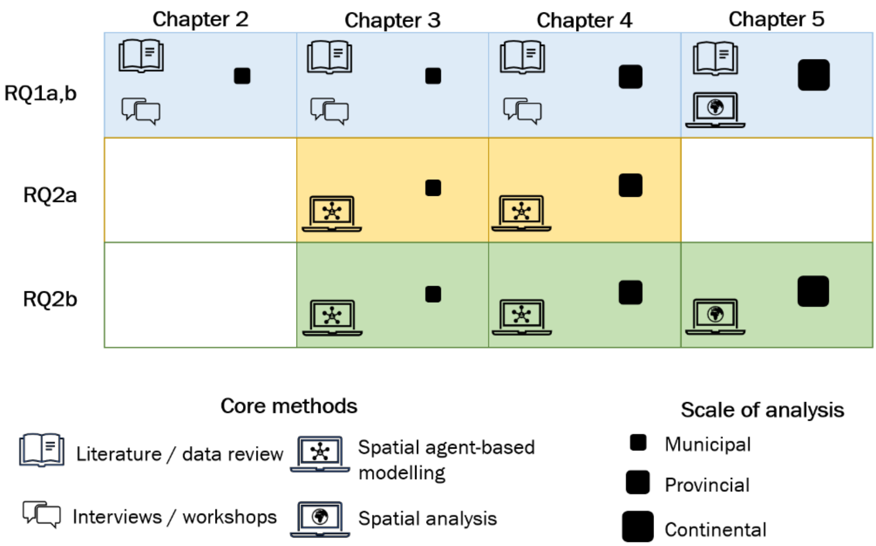

Figure 1.2 – Structure of thesis chapters in relation to the stipulated research questions, core methods of investigation, and spatial scale of analysis.

Chapter 2

Perspectives of farmers and tourists on agricultural abandonment in east Lesvos, Greece

This chapter is published as: Zagaria, C., Schulp, C. J. E., Kizos, T., & Verburg, P. H. (2018). Perspectives of farmers and tourists on agricultural abandonment in east Lesvos, Greece. *Regional environmental change*, 18(5), 1467-1479. https://doi.org/10.1007/s10113-017-1276-4

Abstract

Multi-stakeholder perceptions of landscape changes are increasingly recognized as essential inputs to discussions on future landscape developments, particularly when addressing the future of European rural areas experiencing agricultural abandonment. This research presents a case exploration of abandonment of olive plantations in east Lesvos, Greece. We conducted two sets of semi-structured interviews to relate an exploration on local farmers' ability and willingness to maintain the plantations, to the results of a landscape preference survey undertaken with tourists. Three farmer types are identified following a cluster analysis based on attributes of individual ability and willingness to farm. Farmers belonging to the prevalent type revealed low ability and willingness and expect to further extensify their farms. The remaining two farmer types have higher willingness; they are motivated by cultural reasons, more frequently expressing a desire to maintain their land under family ownership, and partake in social cooperative initiatives promoting practices valorizing the olive plantations. We outline how these types interact with regional drivers of change, and partly also contribute to persistence of abandonment through constrained ability to farm. Abandonment does not align with current landscape preferences of tourists, who favor cultivated landscapes, elements of traditionality within built infrastructure and undertake nature-based activities. We discuss how high willingness to farm associated with professional and pluri-active forms of farming may however provide opportunities to maintain the cultivated landscape and synergize with (agri-)tourism demand. Our findings are comparable to those of other European studies, contributing to discussions on the future of its rural landscapes.

2.1. Introduction

European agricultural landscapes are increasingly defined as multifunctional, recognized for their multiple roles in producing materials, conserving the environment and sustaining rural vitality (Kurkalova, 2005; Van Zanten et al., 2014; Wilson, 2008). The European Landscape Convention, adopted in 2000, played a role in formalizing and promoting this recognition by calling for an integrated framing of landscape assessment and management, where the landscape is defined as a material manifestation of complex human-environment dynamics in a given place, as perceived by a given observer (Council of Europe, 2000; Pinto-Correia & Kristensen, 2013). This approach has been implemented in regulatory policy as well as in more persuasive and educational measures (Primdahl et al., 2013). Implementations have acknowledged the role of both landscape manager and user in shaping the landscape, changing the physical environment and public perceptions of "rurality" (Fyhri et al., 2009; Sayadi et al., 2009).

Acknowledgement of the multiple services provided by agricultural landscapes mirrored the emergence of novel agricultural transitions diverging form solely productivist landscapes. Agricultural re-structuring towards non-commodity land outputs has been seen, for example, in the utilization of agricultural spaces for leisure (Buijs et al., 2006; Oliver & Jenkins, 2003). Wilson (2008), differentiates between cases of "weak" to "strong" multifunctionality, where, under strong multifunctionality, societal values, demands and agri-environmental functioning align. He hypothesizes extensively farmed upland areas of high conservation value within developed countries have high potential for strong multifunctionality, partly due to higher frequency of pluri-active farmers engaged in supporting tourism and landscape protection.

Agricultural restructuring in upland farming areas, however, has often resulted in marginalized territories witnessing economic decline and public disinvestment (Rizzo, 2016). European projections forecast agricultural abandonment as a dominant land use change trajectory in the forthcoming twenty years, particularly affecting mountainous, remote regions characterized by extensive, smallholder systems (van der Zanden et al., 2017).

This process imposes important, context-dependent, ecological and societal trade-offs (Munroe et al., 2013; Renwick et al., 2013) which include implications for biodiversity, carbon storage (Plieninger et al., 2014; Stürck et al., 2015), recreation, cultural heritage, forest fire vulnerability and soil and water resources (Beaufoy, 2001; Sayadi et al., 2009; van der Zanden et al., 2017). As a result, a policy debate has emerged on how to best manage this transition, favoring the preservation of the cultivated landscape or the support of rewilding processes. This decision is inevitably rooted (and complicated) by the different, dynamic perceptions and values attributed by people to the landscapes in question (Navarro & Pereira, 2015).

The former municipality of Gera (87km^2), situated in east Lesvos (Greece), presents a mountainous rural region experiencing abandonment. Gera's olive-dominated landscape is changing towards a Mediterranean-type forest, averaging land conversion rates of 34ha/year over the last 50 years, while experiencing rural depopulation (Bürgi et al., 2015; Kizos & Koulouri, 2010). The olive landscape has been defined as traditional due to the widespread and longstanding presence of the plantations, remnants of heritage elements including dry stonewalls and terraces within smallholder systems, and prevalence of manual labor over mechanization (Kizos & Koulouri, 2006).

Extensive research has taken place in the region to identify: (1) regional drivers of landscape change (Kizos & Koulouri, 2006, 2010; Kizos & Spilanis, 2008), (2) heterogeneous groups of olive-producing farmers and farm types (Giourga et al., 2008; Kizos et al., 2010; Kizos & Koulouri, 2010), (3) different management practices altering landscape features on the farm (Kizos et al., 2010; Kizos & Koulouri, 2006, 2010), and (4) how changing features at the farm scale result in aggregate processes of transformation in the overall landscape (Kizos et al., 2010; Kizos & Koulouri, 2006; Kizos & Spilanis, 2008). These can be interpreted as four steps in a sequenced exploration of regional landscape change through the analysis of farm-scale dynamics. While insight has advanced in each of these focus areas, linking processes between steps (1), (2) and (3), i.e. how actors are influenced by regional drivers to undertake specific actions on the landscape, demand additional research. Importantly, previous studies revealed a farmer classification based on household dependency on agricultural incomes alone is a poor predictor for different managerial strategies, and thus observable landscape changes. Different farmer decision-models are needed, able to capture the role of place attachments held by farmers to the cultivated landscape and accurately weigh the influence of regional drivers upon faming dynamics (Kizos et al., 2010).

These novel decision-making models may reveal whether farmers are able and/or willing to maintain the cultivated landscapes, and in which conditions. A question which arises is how these landscape changes may be perceived, and in-turn impacted by, non-farmer landscape users. Lesvos has limited social and economic development opportunities beyond tourism, yet this sector remains underdeveloped, not having witnessed the mass-tourism character of other Greek destinations (Giourga et al., 2008; Loumou et al., 2000). The "tourism centers" of the island have been associated with more stable population numbers and lower rates of abandonment (Loumou et al., 2000). Studies report this occurs as tourism provides a means of both on- and off-farm income diversification for farmers. The importance of complementary off-farm employment is notable in the number of pluri-active farmers in the region. The latest population census (2011) identified a discrepancy between the 350 individuals (21% of Gera's population) with primary occupation in agriculture and 1538 active farms. On-farm income diversification through agri-tourism has been promoted by regional authorities. Despite successfully increasing incomes, agri-tourism has failed to truly integrate activities within the cultivated landscape and associated traditional products (Gousiou et al., 2001). An influence of tourism on landscape composition has been suggested, yet there has been no clear assessment of demand by this user group for cultivated landscapes in particular, especially uncertain as greatest influence is being witnessed not inland but rather in proximity of coastal centers.

Discussions on interventions addressing the future of European rural landscapes experiencing abandonment demand an understanding of the multifunctional potential of these spaces, partly determined by the demands and perspectives of affected landscape makers and users. Through this case study, we aim to identify if and how olive farmers in East Lesvos are able and willing to maintain the cultivated landscape, and discuss how the landscape changes which ensue from their actions relate to landscape preferences of tourists. Following a presentation of conceptual and methodological backgrounds, the paper is structured around its three objectives: (1) to construct a farmer typology based on individual attributes outlining ability and willingness to farm, characterizing the decision-making behavior of local farmers, (2) to explore how the identified farmer types undertake actions on the landscape with implications for abandonment or maintenance of the cultivated landscape, and (3) to provide a preliminary investigation on the landscape preferences of tourists, relative to the landscape change trajectories identified in East Lesvos.

2.1.1. Conceptualizing landscape change in east Lesvos

Landscapes of change – We differentiate between landscape changes occurring at the farm-scale to changes at the regional scale caused by the cumulative influence of farmer actions. Farmer actions can be clustered in four separate groups: intensification (increasing inputs, frequency of management), diversification (construction of agri-tourism infrastructure, switch to mixed cultivation), expansion, or disinvestment (extensification, sale, abandonment). These actions are reflected in the primary change trajectories identified within olive-dominated plantations in east Lesvos: abandonment, diversification and agricultural intensification (Kizos & Koulouri, 2010) (see Supplementary Information (SI) for a comprehensive description of Lesvos-based/Mediterranean olive plantation typologies identified in literature, and related change trajectories).

Drivers of change – Abandonment is partly driven by declining *olive oil prices* and a difficulty in intensifying mountainous (poorly accessible) smallholder olive plantations (Bürgi et al., 2015). This has contributed to a declining perception of farming as a desirable profession for younger generations. Farmers are also heavily reliant on *agricultural subsidies*, however age and agricultural income dependency requirements for some subsidies exclude a portion of retired and pluri-active farmers (Kizos & Spilanis, 2008). *Demand* *for (agri-)tourism services* has resulted in some plantation clearing for agri-tourism development, and housing pressures particularly near coastal centers (Kizos & Koulouri, 2010). It furthermore provides opportunities for off- and on-farm income diversification to farmers. Declining levels of social capital also play a role, as "traditional" farmer *cooperatives* with political affiliations are distrusted. Novel, "social" cooperative forms are emerging, centred on promoting cultural values associated with the landscape to boost profitability and employment (Bürgi et al., 2015; Shaw, 2017).

Actors of change – The primary actors of change in the region are farmers and tourists. We define farmer decision-making from attributes of ability and willingness to farm. Ability hereby refers to the conditioning factors of the farmer (e.g. age, agricultural training), while willingness addresses the farmer's intentions and values, including cultural motives (Valbuena et al., 2010). These attributes are influenced by regional drivers of change which constrain and define periodic managerial decisions faced by farmers. Tourists are the second focal actor group, impacting the landscape by establishing a demand for specific (agri-)tourism services and playing a role in the valorization of the local landscape.

2.1.2.Methodological overview

Figure 2.1 illustrates how our three objectives address characteristics and interactions between actors (farmers and tourists), regional drivers and landscape changes at multiple spatial scales. The farmer typology developed in our first objective is based on structured interviews with 100 farmers analyzed through cluster analysis. The construction of actor typologies is a common means to study landscape dynamics (Bohnet, 2008; Bohnet et al., 2011). Endogenous characteristics of actors (including motivational, managerial or financial attributes) are identified and actors subsequently grouped to synthesize heterogeneous actions undertaken in response to drivers (Valbuena et al., 2010). Our second objective addresses how and if attributes of the identified farmer types explain past and expected individual actions on the landscape, contributing to regional landscape change. We build on the original framework by Valbuena et al. (2010) and add a second actor group (tourists), responding to landscape changes and influencing regional demand for (agri-)tourism services. Landscape preference studies have used simple rankings (Fyhri et al., 2009; Sayadi et al., 2005) as well as complex choice experiments (Hasund et al., 2011; Rambonilaza & Dachary-Bernard, 2007). Our third objective, scoping landscape preferences of 63 tourists, is a first step in delineating how landscape users respond to and influence landscape change.

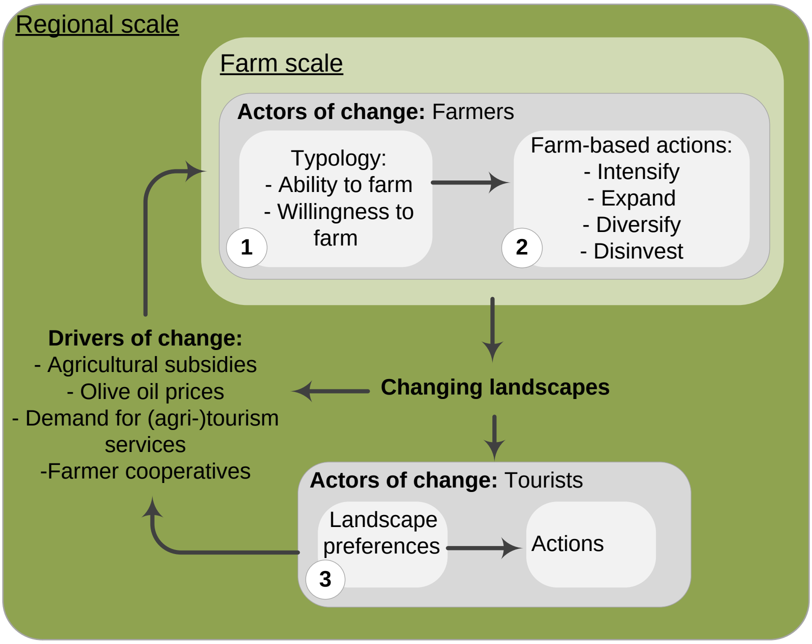

Figure 2.1 – Research framework illustrating how our three objectives address characteristics and interactions between actors (farmers and tourists), regional drivers and landscape changes at multiple spatial scales (adapted from Valbuena et al. (2010)).

2.2. Methods

2.2.1. Farmer interviews

One-on-one interviews were carried out with 100 farmers in Gera between June and September 2015. Results obtained on farming system composition and management in our sample are largely in line with existing data, with over-representation of farmers managing arable land in addition to olive plantations (see SI).

2.2.1.1. Surveying procedure

Respondents were approached in public spaces (bars, cafés, etc.) in the six villages of Gera: Mesagros, Palaiokipos, Papados, Perama, Plakados and Skopelos. Further respondents were recruited via snowball sampling. The interviews lasted between 20 and 45 minutes. They used a seven-part structured questionnaire aiming to describe farmer behavior by investigating defining attributes of ability and willingness to farm (questionnaire sections outlined in **Table 2.1**, questionnaire in SI). Explanatory comments made by the respondents throughout the interview process were noted.

2.2.1.2. Analysis

Survey results from 100 valid interviews were initially explored using Pearson's correlation. Variables describing the individual knowledge sources, actions on the farm, current land uses and perspectives on the future of the local agricultural sector were each aggregated into overarching classes (see **Table 2.1**) to limit the number of variables for analysis (e.g. statements for past owned and/or rented area increase in survey section C.1 were both aggregated under "farmer has expanded system in past"). "Cultural drive" was also defined by multiple survey entries: willingness to pass land onto successors, unwillingness to loose ownership of land and possession of inherited land. This characterization was substantiated by past research, in the region, stating the importance of land "not as assets, but as family capital and something you have to take care for the next generation" (Kizos et al., 2010), and elsewhere in Mediterranean traditional olive orchards (Duarte et al., 2008). "Management intensity" was characterized by use of fertilizers, pesticides, herbicides, irrigation, mechanization, tree density, marketing channel, terrace and stonewall maintenance, annual yield and agricultural income and hired and/or family labor, standardized to give a single summated score of intensity.

9 variables (numbered in **Table 2.1**) were used as input for a hierarchical cluster analysis using complete linkage (furthest neighbor) with squared Euclidian distance, with the aim of grouping farmers in a typology based on individual attributes relating to ability and willingness to farm (following the criteria selection outlined in Valbuena, Verburg, and Bregt (2008)). The

clustering variables addressed a farmer's: ability through their level of professional engagement in agriculture, education, experience from agricultural trainings and use of external knowledge sources. Farmer willingness was addressed through cultural drive and perspective on the future of the local agricultural sector. Social cooperative membership was used as a clustering variable determining both farmer ability *and* willingness, as these cooperatives serve as knowledge exchange platforms and promote landscape conservation and valorization. After cluster analysis, clustering variables and resulting farmer types were investigated via Discriminant Function Analysis (DFA), a commonly applied method for interpretation of clusters, indicating whether and how farmer types vary in relation to each clustering variable (Hair et al., 2010).

Additional *non*-clustering variables were tested for significant differences amongst farmer types. This served to both validate the derived clusters (Hair et al., 2010) (assessing how these newly revealed differences relate to the constructed types) and also evaluate if individual farmer attributes of ability and willingness in turn relate to differences in farm composition and farming strategies (actions outlined in **Figure 2.1**). Depending on their data type, non-clustering variables were analyzed using the chi-square test, one-way ANOVA with Games-Howell post-hoc test or multiple regression analysis (see **Table 2.1** for a comprehensive description and characterization of all clustering and non-clustering variables). For the investigation of regional driving forces, word counts were recorded identifying opinions on (traditional or social) cooperative membership and sentiments on current government support for the agricultural sector (within explanatory comments to survey questions D.2, D.9, D.10, F.1, H.4).

Table 2.1 – Description and characterization of (1) variables used for clustering farmer types and (2) non-clustering variables analyzed statistically.

	Survey question(s) used for variable derivation	Variable description and characterization	Data type	Determinant of ability / willingness / action
Clustering variables	D.1, D.2: "Professional engagement in agriculture"	(1) Full-time (2) Pluri-active (i.e. receiving additional incomes outside of sector, excluding pensions)	Binary	Farmer ability
	D.7: "Education"	(3) High school level diploma obtained (or equivalent)	Binary	Farmer ability
	D.8: "Agricultural training"	(4) Farmer has received formal agricultural training	Binary	Farmer ability
	G.1: "External knowledge usage"*	(5) Farmer makes use of cooperatives, the internet, consultants and/or research organizations when seeking advice on farm decision-making	Binary	Farmer ability
	D.9: "Social cooperative membership"	(6) Farmer is a member of a local, social cooperative	Binary	Farmer ability / Farmer willingness
	H.4: "Perspective on future of local agricultural sector"*	(7) Farmer perspective is pessimistic (8) Farmer believes pluri-activity will be necessary	Binary	Farmer willingness
	D.5, H.3: "Cultural drive"*	(9) Farmer has inherited at least part of his land and has expressed both a desire to pass it onto successors and reluctance to sell	Binary	Farmer willingness
Non-clustering variables	D.3: "Farmer age"	-Farmer age	Continuous	Farmer ability
	D.10: "Subsidies received"	-Farmer receives subsidies (not including the Single Farm Payment (SFP))	Binary	Farmer ability
	D.9: "Traditional (non-social) cooperative membership"	-Farmer is a member of a local, traditional cooperative	Binary	Farmer ability
	G.1: "Internal knowledge usage"*	-Farmer makes use of own experience, experiences of neighbors and/or family members when seeking advice on farm decision-making	Binary	Farmer ability
	E: "Household composition"	-Farmer has successor working on the farm	Binary	Farmer ability/willingness
	H.2: "Influence of declining profits"	-Farmer refuses to ever quit farming despite consistently declining profits	Binary	Farmer willingness

	H.4: “Perspective on future of local agricultural sector”*	-Farmer perspective is optimistic	Binary	Farmer willingness
	C.1: “Past actions”*	-Farmer has intensified system in past -Farmer has expanded system in past -Farmer has diversified system in past -Farmer has disinvested system in past	Binary	Farm action
	H.1: “Future actions”*	-Farmer will intensify system in future -Farmer will expand system in future -Farmer will diversify system in future -Farmer will disinvest system in future	Binary	Farm action
	B.1: “Current farm area”	-Total farmland area	Continuous	Farm action
	B.4, B.5: “Current land use”* "	-Mix built -Mixed agriculture with no understory cultivation -Mixed agriculture with understory cultivation -Olive orchards and grazing land only -Olive orchards only	Categorical	Farm action
	B.6 – B.10, E.1, F.1: “Current management intensity”*	-Farm management intensity	Continuous	Farm action
	B.5: “Organic production”	-Farm is certified organic	Binary	Farm action

*Composite variables constructed from answers of multiple questions (survey question codes listed in SI)

Note: only the affirmative description is provided for binary (yes / no) variables.

2.2.2. Landscape preference survey

The landscape preference survey addresses landscape use complementarily to the analysis of farmer decision-making and landscape "production". It investigates landscapes shaped by farmer actions, where disinvestments are associated with de-intensified landscapes and investments are portrayed in cultivated landscapes. Built landscapes were investigated to probe whether tourist preferences relate to elements of traditionality (seen in local architecture as well as in plantations) (Kianicka et al., 2006) and shed preliminary insight on the potential effect of built infrastructure as a result of increased off-farm activities. Coastal views, livestock and other cultivations were excluded as these represent minor and non-rising farming strategies, or could provide bias. Landscapes were categorized following consultation of academic literature, Panoramio and Google Maps Satellite and Street View imagery, exploratory field visits and interviews with local scientific experts (complementing work from Beaufoy (2001); Fleskens (2008), see SI). The approach aimed to distinguish landscapes at varying scales, so that preferences could be elicited towards view-sheds and immediately surrounding landscapes to define overall landscape perception (Karjalainen & Tyrväinen, 2002).

18 photos (shown in SI) were selected following consultation with a local scientific expert. The photographs were subdivided into four sets. Sets 1 and 2 illustrate cultivated to progressively abandoned olive plantations, sets 3 and 4 show increasing housing sprawl and urbanization in forested areas. The duplication of sets for the same landscape change trajectory offered a validation mechanism for stated preferences. Each photograph within a set illustrates a different stage of the trajectory. To eliminate bias from terraces and slope, set 1 presents photos from non-sloping, non-terraced regions, while set 2 illustrates photos of sloping and terraced systems.

2.2.2.1. Surveying procedure

Interviews took place between June 22 and June 26 at the departure point of Mytilini Airport, engaging with 63 international and national tourists that had visited the island. On average, four international flights departed from the airport between 10AM and 6PM on each of the interviewing days in addition to national flights. The interviewer was present at least two hours prior to the departures and approached all passengers in the waiting lounge. Although our sample does not allow for representativeness, the regularity of charter flights throughout the summer months make the selection of our sample adequate (see SI). Interviews were carried out in English and lasted between 4 and 10 minutes. Respondents were initially asked to freely describe the landscapes of the island, and to specify which natural or cultural features they found particularly striking. Subsequently, they were presented with the first set of photographs in a randomized order and asked to rank them based on visual preference. Next, the respondents were asked to briefly state the motivation behind their election of most and least preferred choices. The exercise was repeated for the remaining sets. Questions on personal details followed and additional relevant comments made noted (questionnaire in SI).

2.2.2.2. Analysis

Descriptive statistics were used to describe the tourist sample and the ranking score of each landscape photograph. The Wilcoxon Signed-Rank Test was used to verify consistency of means of matching photographs between coupled sets, validating the stated landscape preference or revealing potential sources of bias. A respondent-specific preferred ranking *order* score was calculated for each abandonment set, enabling an understanding of whether respondents ranked photographs in relation to the re-forestation/abandonment vs. cultivation construct (see SI). These scores were investigated in terms of frequency distributions and Pearson's correlation. Explanatory comments supporting ranking scores revealed additional insight on preferences. Open descriptions of the island were explored by means of word counts comparing mentions of natural (biophysical) vs. built features. Mentions of olive(tree)-related attributes were also counted. All statistical analyses was conducted in SPSS v23.

2.3. Resuts

2.3.1. Gera's olive farmer typology: attributes of ability and willingness

The cluster analysis resulted in three farmer types characterized as disengaged farmers, active part-timers, and professional farmers (**Table 2.2**). DFA revealed Functions 1 and 2 (discriminating the groups) account for 89.1%

and 18.1% of the variance with canonical correlations of 0.906 and 0.708, and eigenvalues 4.555 and 1.008 respectively. Function 1 discriminates disengaged farmers from the other two farmer types, while function 2 discriminates the active part-timers from the professional farmers. Professional engagement in farming (full-time vs. part-time or pluri-active) and education are the highest loading variables on discriminant function 2 and 1 respectively, representing important contributing variables to group separation. Test of equality of group means determined two clustering variables to be non-significantly different amongst groups (**Table 2.2**).

- *Disengaged* farmers constitute the predominant type within our sample. They are mostly part-time engaged in agriculture, with approximately one-third full-time farmers and only a few pluri-active farmers. This cluster represents farmers that have not obtained high-school level education. Their ability to farm is constrained by their part-time engagement in agriculture, lowest attendance to formal agricultural trainings and use of external knowledge sources. Their willingness to farm and maintain the cultivated landscape is also lower than that of the remaining identified groups; disengaged farmers rank lowest in social cooperative membership and cultural drive, and highest for pessimistic views on the future local agricultural sector.
- The *active part-timer* type is characterized by farmers with multiple income activities and a remaining group of part-timers mostly comprising retirees. Non-agricultural incomes derive from a wide range of sources: tourism, employment in the army, local shops and within fishery, forestry, construction and education sectors. Active part-timer's ability to farm is strengthened by high attendance to formal agricultural trainings and education. Few are social cooperative members, yet they are willing to keep farming for cultural motives, as this group has the highest proportion of culturally driven farmers. They believe pluri-activity will be successful and vital to the survival of the local agricultural sector.

- *Professional* farmers are mostly full-time farmers with no pluri-active members. They are the most educated, attend formal agricultural trainings and consult external sources, contributing to a high ability to farm. This group's high willingness to farm and maintain the cultural landscape is demonstrated in the highest proportion of social cooperative members, strong cultural drive and lowest share of pessimists.

Table 2.2 – Distribution of farmers over (non-)clustering variables defining farmer ability and willingness to farm, listed per identified cluster group. Both DFA functions are significant at p < .001 (see SI for full results on non-clustering variables).

Cluster group / Farmer type	1 Active part-timers	2 Disengaged farmers	3 Professional farmers	Equality of group means (significance)	DFA Function 1	DFA Function 2
No. of farmers	27	49	24			
% Composition per clustering variable						
(1) Full time engagement in agriculture	0	35	75	.000	.021	-.673
(2) Pluri-active engagement in agriculture (i.e. receiving additional incomes outside of sector, excluding pensions)	67	16	0	.000	.107	.678
(3) High school diploma obtained (or equivalent)	82	6	100	.000	.756	-.160
(4) Farmer has received formal agricultural training	26	8	25	*.070*	.111	.022
(5) Farmer makes use of external knowledge sources	78	49	67	.039	.115	.098
(6) Farmer is a member of a local, social cooperative member	11	2	29	.002	.146	-.201
(7) Farmer perspective is pessimistic on the future of the agricultural sector	56	61	42	*.294*	-.061	.093
(8) Farmer believes pluri-activity is necessary to maintain the future agricultural sector	93	76	63	.036	.010	.264
(9) Farmer is culturally driven	74	39	71	.002	.169	-.045
%* Composition per non-clustering variable				**Sig.**		
-Farmer age (*average age in years)	51	60	48	.003		

-Farmer receives subsidies (not including the SFP)	26	14	33	*.157*	
-Farmer is a member of a traditional (non-social) cooperative	37	41	33	*.863*	
-Farmer makes use of internal knowledge sources	93	98	92	*.508*[a]	
-Farmer has successor working on the farm	15	12	17	*.931*[a]	
-Farmer refuses to ever quit farming despite consistently declining profits	89	73	50	.007	
-Farmer perspective is optimistic	85	80	89	*.698*[a]	

Italicized: differences in variable values across cluster groups are non-significant.

Underlined: variables most highly contributing to group separation.

[a] Do not meet assumption for chi-square test, expected counts too low.

Analysis of the farmer typology with non-clustering variables relating to ability and willingness partly validate the identified types and provide additional insight on farming dynamics (**Table 2.2**). Significant relationships were found between farmer typology and age ($F(2, 97) = 6.162$, $p < .005$) with older farmers in the disengaged group than in the active part-timer and professional groups. The average age of farmers interviewed was 54 years. The professional type holds the highest proportion of young farmers (30% <35, 68% <50), while disengaged farmers have an opposing distribution with 68% above 50. These relate to the clustering variables respectively attributing a high and low ability to farm to professional and disengaged farmers.

Traditional cooperative membership, presence of successors working on the farm, use of internal knowledge sources, and optimistic outlook did not vary significantly among farmer types. Over 80% of farmers in all types agreed with optimistic statements about the future of the local agricultural sector (lowest proportion amongst disengaged). Over 90% in all groups relied on internal knowledge sources (family members, neighbors, own experience) when undertaking farm-based decisions. Less than 20% of farmers in all groups had successors presently working on the farms. The majority of farmers in all groups decided not to subscribe to traditional cooperatives. Of these, over a quarter explicitly expressed criticism throughout the interview, as exemplified by Farmer 16 characterizing them "a total failure", Farmer 41 as "deeply corrupted, cheat producers" and Farmer 17 stating they "do not function as cooperatives, rather as businesses". 21% of member farmers specified they were "passive" members, e.g. Farmer 31 stated cooperatives are only useful if viewed as being part of "tradition […] for storage, promotion, sales".

A minority of farmers in all groups receive subsidies (excluding the SFP), particularly among disengaged farmers (14% alone are recipients), while enabling professionals' ability to farm to greater extents (33% recipients). At least half of the farmers in all groups refuse to quit farming despite continuously declining profits, highest among active part-timers, confirming their strong willingness to farm due to cultural motives. Professionals are more reluctant to continue farming professionally under increasingly unprofitable conditions, despite also holding strong cultural motives. This is likely attributed to higher dependency on agricultural incomes. Culturally-driven farmers expressed elements of pride by commenting on Gera's high-quality olive oil (Farmer 26: "most prized") and soil. They further recognized the role the olive sector plays in the maintenance of local cultural heritage (Farmer 38 referred to the preservation of monuments in olive fields) and the potential of linking these values to tourism (Farmer 1: "traditionality will make the difference").

2.3.2. Relating the farmer typology to past, present and future actions on the farm

One-way ANOVA revealed a significant relation between farmer type on farming intensity ($F(2, 97) = 4.337$, $p < .05$) with higher intensity ratings among professionals than disengaged farmers. A significant regression model was found ($F(9,86) = 3.37$, $p < .05$, $R^2 = .26$) when predicting the management intensity score from clustering variables, showing social cooperative membership (*Beta* = .25, t(86) = 2.35, $p < .05$), cultural drive (*Beta* = .21, t(86) = 2.09, $p < .05$) and full time engagement in agriculture (*Beta* = .25, t(86) = 2.32, $p < .05$) as the significant predictors. 8 farmers explicitly acknowledged the important role of social cooperatives for "traditional" product promotion through novel certification schemes supporting integrated pest management and enabling access to new markets. Overall, 51% of farmers were classified as low-intensity, 40% as medium and 9% high intensity management. The professional group comprised more organic farmers than the others ($x^2(2) = 6.05$, $p < .05$). Farm area and land use did not vary significantly among farmer types.

Figure 2.2 compares trends between past and intended actions amongst the farmer types. All types have similar patterns in past actions. Most frequent is intensification, followed by expansion and diversification with very few disinvestments. The disengaged type scores higher on past disinvestment than others, while professional farmers have the highest proportion of past investors. Disengaged farmers also have fewer cases of past intensification and diversification, while active-part timers the lowest proportion of past expansionists.

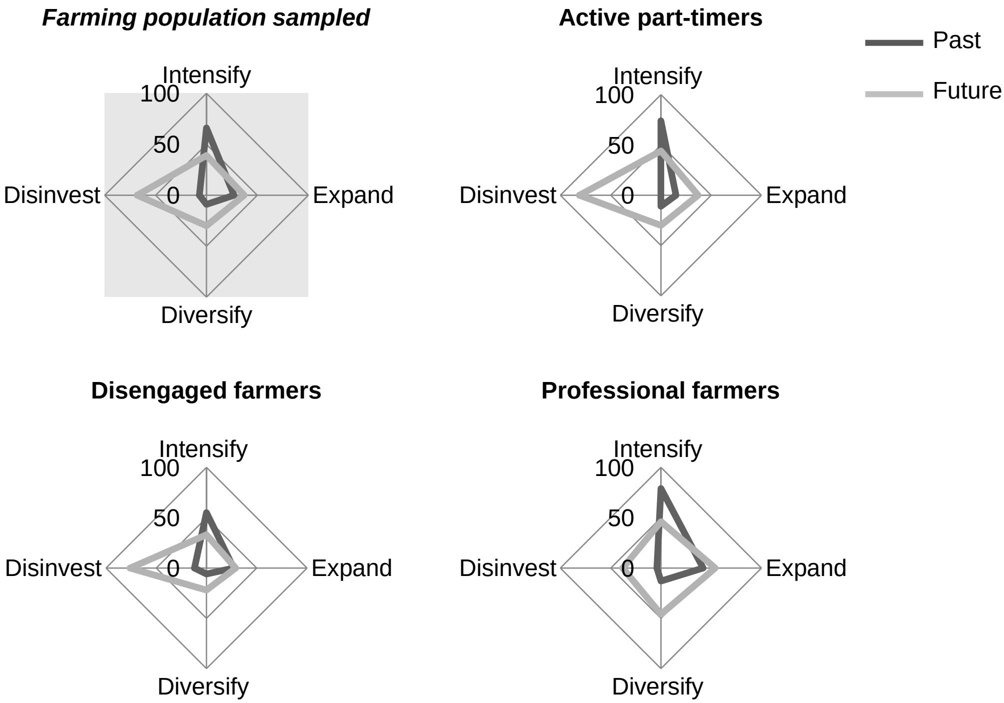

Figure 2.2 – Frequency (%) of past decisions and expressed likelihood of future (dis)investments per farmer type and total farming population sampled. Past and future expressed likelihoods of decision are not exclusive.

When comparing past and expressed likelihood of future actions, the most striking difference is the rise in the proportion of farmers expecting to disinvest. Disinvestment is anticipated within the next decade by 68% of interviewees (**Figure 2.2**). Results revealed a higher frequency to disinvest amongst active part-timers (82% of total) than professionals ($x^2(2) = 13.79$, $p <$ .001). 11% of farmers explicitly specified a lack of government support, declining (and poorly promoted) subsidies and the financial crisis have contributed to declining profits in the olive sector and thus farm investments. Farmer 48 states "sometimes the harvest costs are bigger than the product's sale, so many people leave them [the olives] on the ground", while Farmer 4 cannot afford consultancies and Farmer 61 stopped purchasing fertilizers.

Further specifications relate to disinvestments occurring gradually, beginning on least accessible plots.

When investigating individual actions in isolation, the only short-term action to gain a positive mean score on the Likert scale (average 4.24, agreement scale 1 to 5) was "continue with current farming system". Future and long-term *sectorial* sentiments however showed a prevailing agreement with positive statements of *change*, relating notably to olive oil markets becoming competitive again and conservation being recognized (positive outlook, **section 2.3.1**), with lowest mean Likert expressed for the continuation of abandonment (2.92). A discrepancy between present realities and expected future actions is witnessed also in the uptake of the farm by successors; only 14% of farmers have successors actively working on the farm, yet 76% agree with the statement: "When I retire, I will pass my land onto a successor".

2.3.3.Characteristics of interviewed tourists

Under the land zoning by Kizos and Koulouri (2006) results found 33% of respondents lodged in the eastern part of the island dominated by olives. Tourists combined beach-based activities with inland explorations. The most common activities were beach-based (over 75% of respondents), visiting towns and villages (57%) and hiking and trail walking (33%), in line with findings by Papanis and Kitrinou (2011). When asked to freely describe the environment(s) of Lesvos, 22% of respondents mentioned the presence of olive trees. While 81% of respondents referred to natural, or biophysical, attributes (e.g. topography, diversity in vegetation), only 11% referred to anthropogenic or built elements (e.g. villages, architectural styles), and 17% of respondents solely provided subjective descriptions (e.g. beautiful, interesting).

2.3.4.Tourist landscape preferences: ranking scores and ranking order

The photographs with the highest mean ranking score per set, and thus preferred, were: (B) *intensively cultivated plantation* and (E) *traditionally cultivated plantation* for the abandonment sets, and (I) *mixed forest* and (P) *scattered housing* for housing sprawl sets. The photographs with the lowest mean score per set, and thus least preferred, were: (D) and (H) *abandoned field*,

(K) *scattered housing* and (R) *city* (**Table 2.3**). Preferred landscapes have lowest standard deviations in both sets. Results for urbanization (set 4) demonstrate a preference for natural or low-density housing landscapes, as the city landscape was least preferred by 75% of respondents. Results from set 3 differ, as the landscape depicting a densely built village received highest counts for both highest and lowest ranking scores. Validation of stated preferences for the abandonment sets (results of the Wilcoxon Signed-Rank Test) illustrated consistency in ranking position for abandoned and neglected plantations (43% of respondents marked abandonment in the same ranking position in both sets), but significant differences for traditional and intensive plantations. An analysis of ranking *order* revealed both sets 1 and 2 have a majority of respondents preferring cultivated landscapes and disfavoring abandoned ones (63.5% of interviewees in set 1 and 68.2% in set 2). Pearson's correlation similarly revealed a positive relationship between preference score and frequency in set 2 ($r = 0.639$, $p < .05$) (see SI).

Table 2.3 – Standard deviation, mean and median score per ranked landscape photograph, listed separately for sets illustrating processes of abandonment (sets 1 and 2) and housing sprawl (sets 3 and 4) in descending order of preference. Note: values for sets 1 and 2 are based on ranked scores with maximum values of 4 while sets 3 and 4 on maximum values of 5.

	Photo ID	Photo description	Mean score	St. Dev.	Median score
Ranked by mean average ranking- Sets 1 and 2	B	*Intensively cultivated plantation*	3.06	0.93	3
	E	*Traditionally cultivated plantation*	3.00	1.12	3
	G	*Neglected plantation*	2.71	0.96	3
	C	*Neglected plantation*	2.67	0.97	2
	F	*Intensively cultivated plantation*	2.54	1.00	3
	A	*Traditionally cultivated plantation*	2.43	1.16	3
	D	*Abandoned field*	1.84	1.07	1
	H	*Abandoned field*	1.75	1.02	1
Ranked by mean average ranking- Sets 3	P	*Scattered housing*	3.46	1.22	3
	N	*Mixed forest*	3.44	1.24	4
	O	*Olive forest*	3.40	1.26	3
	I	*Mixed forest*	3.24	1.29	3
	J	*Olive forest*	3.11	1.22	3

Q	*Suburb*	3.11	1.23	3
L	*Sparsely built village*	3.10	1.39	3
M	*Densely built village*	3.06	1.77	3
K	*Scattered housing*	2.49	1.27	3
R	*City*	1.59	1.19	1

The ranking order results demonstrate a significant majority of tourists understand and value the landscape representations under the cultivation vs. abandonment construct. This is further exemplified in the justifications provided by the tourists for preferring cultivated landscapes. Tourists valued elements of typicality (Tourist 41 "I see Greece"), human influence and order. Abandoned landscapes were coherently appreciated by fewer tourists because they did not exhibit human influence. They were valued as more (and more diversely) vegetated, less monotonous, regulated and artificial. Responses of tourists that did not show consistency in their preference scores between first and second sets point towards some bias in the photographs (Tourists 3 and 16 stated preference based on "greenery" and 7 on "overall view preference") while others stated preferences on impulse (Tourist 22 "very instinctive"). Correlating preference scores against covariates revealed no significant relationships.

Mean ranking scores and ranking order results for housing sprawl sets revealed preferences for an optimal level of housing. Only 25% of respondents preferred natural to built environments. Fewer (13%) respondents ranked both nature landscapes last and favored built environments. Explanatory descriptions for housing sprawl sets suggest preferences for a balance of both worlds, exemplified by Tourist 28 valuing the "contrast between nature and civilization, mountains and villages, rural and urban impressions". While heavily built-up landscapes were seen as crowded and "too busy for a holiday" (Tourist 56), solely natural viewscapes were disfavored as they evoked negative sentiments of isolation and excluded traditional elements valued within local architecture.

2.4. Discussion

2.4.1. Linking actors, regional drivers and landscape change trajectories

The identified farmer typology revealed a heterogeneous olive-farmer population with significantly different levels of ability and willingness to farm. Disengaged farmers (majority group) were defined by both low ability and willingness. Conversely, active part-timers and professional farmers have high ability and willingness, yet important differences in the two attributes exist between these farmer groups. Active-part timers revealed their high willingness to farm as strongly motivated by cultural (rather than solely profit-maximizing) reasons, as seen in their high cultural drive and refusal to stop farming despite steadily declining profits. Professional farmers, despite also stating a high cultural drive and thus refusing to loose ownership of their land, are less reluctant to quit farming as a profession when facing declining profits.

Typology results have implications for farm-level actions and (consequently) regional landscape change while revealing the influence of known regional drivers (**section 2.1.1**). Attributes and actions by each of the farmer types relate to a persistence of abandonment in the landscape, contrasting the stated landscape preferences of tourists as follows:

- Professional farmers' dependency on agricultural incomes, coupled with a refusal to sell land is likely to either result in abandonment if profits decline past acceptable thresholds, or in an eventual transition towards pluri-activity driven by declining incomes rather than a desire to diversify (similar dynamics in Lamarque et al. (2013); Vernimmen et al. (2002)). A reliance of farming strategies upon sectorial profitability and cultural factors is also stated elsewhere in literature (Acosta et al., 2014; Sutherland, 2010; Walther, 1986), where a willingness to maintain land under family ownership and low presence of successors induces abandonment.
- Unlike professionals, active part-timers stated they will continue farming regardless of declining profits. Our results however demonstrate this group is also forecasting disinvestments. This action could be motivated by multiple factors. On the one hand, high average age of farmers in this group (as in the others) hinders ability

and prospects of farm investments. On the other, lack of support and incentives towards this group by operating subsidies may also be acting as a deterrent.

- Disengaged farmers represented our samples' predominant group despite low ability and willingness. Results indicate they do not wish to quit farming despite declining profits, yet they are pessimistic on the future of the sector, more willing to sell their land and more reluctant to pass it on to successors. Giourga et al. (2008) provide partial explanation to this phenomenon, suggesting poor infrastructural development and limited alternative employment opportunities are keeping (unwilling) farmers to the sector. Infrequent use of extension services by disengaged farmers presents a barrier for scaling up successful practices to increase profits. Their low management intensity and high frequency of disinvestments suggest a continuation of extensification and abandonment.

The willful maintenance of the cultivated landscape is thus supported by active-part timer and professional types, constrained by ability rather than willingness to farm. Their high willingness relates positively to tourists' appreciation for olive plantations and nature-based activities, revealing prospects for reversing abandonment through actions of both actor groups. Our results show tourists value local rural settings because they provide elements of traditionality embedded within both cultivated-natural and built-up landscapes. This is in agreement with other tourist landscape preference studies, where results found highest appreciation within (agricultural) cultural landscapes (see Howley (2011); Hunziker et al. (2008); Schirpke, Tasser, and Tappeiner (2013)). In a study by Lamarque et al. (2013) farmers regarded themselves as stewards of the land and thus refused abandonment. Our results similarly saw farmers largely disagreeing with a statement forecasting continuation of abandonment, and revealed elements of land stewardship in the desire to pass land on to successors and actions of social cooperatives. These promote practices favoring conservation of the olive landscape, foster cultural farming motivations and act as knowledge sharing platforms (Bock, 2016; García-Martín et al., 2016; Shaw, 2017).

Regional drivers of change reveal eventual mechanisms for interventions to maintain the cultivated landscape. Municipal, regional and supranational policy may play a role in the development of suitable infrastructure, efficient subsidies and strategic marketing able to valorize local heritage in a culturally sustainable manner (Burton & Paragahawewa, 2011; de Graaff et al., 2008; Mitchell & Barrett, 2015). Subsidies could back farmer pluri-activity, supporting active part-timers in the maintenance of the agricultural-heritage landscape. A formal recognition of the heritage value in Gera's farmed landscape (e.g. through High Nature Value Farmland designation) could further present novel opportunities for collaborations with existing cooperative or non-cooperative institutions, renewing an interest in the development of inland (agri-)tourism.

2.4.2.Reflections on methods

Our approach did not aim to validate statements and discourses with additional data sources. Emphasis was intentionally placed on an analysis of characteristics, actions and preferences of two communities, and how these interact to influence regional landscape change. This decision reflects a need for sustainability sciences to move towards integrated assessments of socio-ecological systems, demanding depended explorations of how actors' perceptions frame interactions with their environment, i.e. the "human feedback mechanisms" (Masterson et al., 2017). Further questions however remain. Our landscape preference investigation indicated some source of bias in the photographs and shed only preliminary insight from a limited sample. Future research may place additional emphasis on tourism behavior (eventually through a tourist typology), addressing the miss-match between landscape appreciation and use. While tourists favored cultivated landscapes, they often undertook activities in town centers and on the coast. Landscape preferences and activities of tourists contrast mass-tourism trends, yet past research has revealed the complexity inherent to the re-production/re-definition of space that comes with agri-tourism also (Figueiredo, 2009; Galani-Moutafi, 2013). Considerations on tourism development are especially relevant amidst a refugee crisis which may disincentivize investments.

2.5. Conclusions

Our farmer typology and preliminary scoping of tourist landscape preferences are suited to inform discussions on the strategic planning of rural spaces, increasingly attentive to areas marked by agricultural abandonment (Soliva et al., 2008). The typology, based on attributes of ability and willingness to farm, confirms the importance of professional engagement in agriculture as a key determinant of group separation (Kizos et al., 2010). Importantly, however, the more comprehensive inclusion of multiple variables, specifically those relating to willingness to farm, explains differences in farm-based actions impacting the regional landscape. Our results revealed the prevalent farmer type is defined by low ability and willingness to farm, and is forecasting disinvestments resulting in further extensification of the landscape. A majority of farmers belonging to the active part-timer and professional types are however willing to maintain the cultivated landscape. An innovative aspect of our work was to relate investigations on different communities through methods often undertaken separately. We found a preference for cultivated over abandoned landscapes by a community often unaccounted for in landscape preference research (van Zanten et al., 2014). The tourism sector may provide options for further valorization of the public goods supplied by the cultivated landscape, supported by cultural farming motives and novel cooperative initiatives. Our assessment is valuable in its preliminary scoping for alternative futures explorations, where conflicting and synergetic dynamics between and amongst actors and landscape change are revealed.

Acknowledgements

We acknowledge financial support from the European Commission FP7 HERCULES project (Grant no. 603447). We thank all survey participants as well as students at the University of the Aegean that were involved in conducting the interviews with farmers. A special thanks to D. Gounaridis, E. Pavlou, E. Bourgia, T. Tzimos, I. Christia and E. Kappa for facilitating this process. We are additionally grateful to anonymous reviewers for their useful comments and feedback on earlier versions of this work.

Chapter 3

Cultural landscapes and behavioral transformations: an agent-based model for the simulation and discussion of alternative landscape futures in east Lesvos, Greece

This chapter is published as: Zagaria, C., Schulp, C. J. E., Kizos, T., Gounaridis, D., & Verburg, P. H. (2017). Cultural landscapes and behavioral transformations: An agent-based model for the simulation and discussion of alternative landscape futures in East Lesvos, Greece. *Land Use Policy*, 65, 26-44. https://doi.org/10.1016/j.landusepol.2017.03.022

Abstract
Agricultural intensification and abandonment have been identified as two of the more prominent and polarizing drivers of landscape change in Europe. These transitions may induce deterioration in landscape functioning and character, particularly in cultural landscapes demonstrative of evolving human-environment dynamics that have sustained environmental benefits through time. Cultural and behavioral motives are important root influences to such landscape transitions, yet efforts to address landscape degradation are often hampered by a failure to account for the heterogeneous decision-making nature of its agents of change and the inherent complexity of socio-ecological systems. Novel techniques are required to further disentangle responses to multi-level drivers and discuss alternative landscape development trajectories. Agent-based models constructed by means of participatory approaches present increasingly applied tools in this context. This study sought to capture and model the future perspectives emerging from presently occurring farming discourses in the region of Gera (Lesvos, Greece), characterized by persistent abandonment of its traditionally managed olive plantations. We constructed an agent-based model iteratively in collaboration with the local farming community and experts in landscape research. Empirical findings informed the model through the construction of a farmer typology, revealing a heavy reliance of the farming community upon sectorial profitability, prevalent cultural farming motives and emerging landscape initiatives. The model examined the de-coupled role of agricultural profitability and landscapes initiatives in shaping the behavior of land managers, mapping alternative landscape futures over a period of 25 years. Model results illustrate both increased profitability and action by landscape initiatives are required to reverse abandonment trends within the simulated time frame. The hypothesized ability of landscape initiatives to maintain and promote a cultural drive amongst adhering farmers is crucial for securing behavioral transformations towards professionalism. This study confirmed agent-based modelling to be intuitively received by stakeholders who significantly contributed to model structure refinement and the rejection of a status quo scenario.

3.1. Introduction

"Cultural landscape" definitions have historically revealed layered and subjective notions, as physical manifestations of cultural and environmental processes are filtered through experiential and intangible values shaping individual beliefs and conceptions (Jones, 1991). Due to the widespread and long-standing influence of human activity across rural landscapes in Europe, such subjectivity implies these landscapes are all likely to be perceived as "cultural" (Tieskens, Schulp, et al., 2017). Distinctions have however been proposed, on the one hand likening cultural landscapes specifically to those traditional, low-intensity agrarian landscapes having sustained valued heritage elements and environmental benefits through time. Importantly, the cultural landscape concept has also been used to identify valued landscape elements increasingly at risk of disappearance (Jones, 1991; Tieskens, Schulp, et al., 2017). Processes resulting in the valorization of cultural landscapes (as the establishment of UNESCO World Heritage Cultural Landscapes (Rössler, 2006)) have occurred alongside processes conversely increasing their vulnerability to declining landscape functioning (Plieninger et al., 2016). Cultural landscapes of the Mediterranean exemplify this dual phenomenon, where despite widespread recognition of the multiple services they provide (Plieninger et al., 2013) traditional agricultural landscapes are gradually being lost to abandonment to the combined detriment of tourism, rural communities and specific ecosystem services (ES) (Fleskens, 2008; Sayadi et al., 2009; Schmitz et al., 2007). As with all landscape transitions occurring in Europe, changing cultural landscapes are a result of dynamic contexts to which societal and behavioral transformations are integral components (Ohnesorge et al., 2013; Plieninger et al., 2013, 2016). Land-based solutions countering deteriorating landscape functioning are often hampered by a failure to account for the inherent complexity characterizing these socio-ecological systems (SESs) (Hoang et al., 2006). Accounting for sociological perspectives in the analysis of cultural landscape change can disentangle this complexity via the identification of actors and organizational properties which catalyze such transformations (Rudel, 2009).

In the context of cultural landscape change there is a need for considering behavioral changes which may ensue as a result of collective action and local initiatives emerging "bottom-up" within communities, alongside changes brought about by large-scale drivers (Selin & Schuett, 2000). This is particularly relevant since the increased emergence of integrated landscape approaches and discourses promoting the fostering of Integrated Landscape Initiatives (ILIs). The definition adopted builds on that of the Landscapes for People, Food, Nature Initiative (LPFN) (Milder et al., 2014) and states that ILIs have to: "work at the landscape scale, involve inter-sectorial coordination, develop or support multi-stakeholder processes, be highly participatory and work mainly on a non-profit basis" while "fostering the provision of a broad range of landscape services" (Plieninger et al., 2014). ILIs stem from an understanding that collaboration amongst institutions at all levels is necessary for fostering the social and cultural capital vital to heritage conservation and sustainable land management (Prager, 2015). Facilitating institutions, such as ILIs, are required to bridge between involved stakeholders, transcending disciplines and scales, and emphasize capacity building for the self-sustainment of feedbacks to social capital building (Cash, 2001; García-Martín et al., 2016; Wagner & Fernandez-Gimenez, 2009).

Integrated or collaborative initiatives have rarely been explicitly incorporated within computational models of landscape change (Doran, 2001). Advances in landscape science have seen emphasis on the development of models in close collaboration with local stakeholders, whether through companion modeling approaches, on-site interviews or stakeholder workshops (Janssen & Ostrom, 2006; Voinov et al., 2016), favoring the use of models for the discussion of local management options and the design of spatially explicit explorations (van Berkel & Verburg, 2012).

Agent-based modelling (ABM) has gained ground in land-use change science precisely as a means to explore management interventions within complex SESs (Filatova et al., 2013). Inherent to ABM research is the placement of the agent, or actor, "center-stage" in determining landscape transitions, setting driving forces as components of an environment within which the actor operates and takes decisions (Hersperger et al., 2010). ABM thus focuses on modeling the behavioral processes and decision-making of agents, representing the diversity within learning, adaptation, imitation and communication processes that characterize heterogeneous communities. Following a delineation of agent attributes and decision-rules representing the dynamics at play within a system, an ABM allows for a summated representation of individual actions at a wider scale, for example demonstrated in regional land-cover transitions. ABMs are valuable in the exploration of alternative landscape futures, where driving forces such as market prices, subsidies and trade regulations can be altered and the resulting impact upon decision-making and land management represented and quantified. Such an approach has been adopted in numerous models, see Gibon, Sheeren, Monteil, Ladet, & Balent (2010); Le, Seidl, & Scholz (2012); Lobianco & Esposti (2010); Schreinemachers & Berger (2011); Valbuena, Verburg, Bregt, & Ligtenberg (2010); Wang, Brown, Riolo, Page, & Agrawal (2013). While ILIs per se have not been investigated through ABM, studies have focused on the spread of organic farming or sustainable land management practices (Johnson, 2015; Kaufmann et al., 2009), yet have rarely incorporated motivational drivers (Kaufmann et al., 2009). The study of behavioral responses to existing drivers may therefore include a comparison of the impact of actions of local mobilization groups to those of macro-drivers (Caillault et al., 2013).

The objective of this paper is to improve our understanding and representation of the interplay between macro-drivers, ILIs and behavioral transformations in the context of cultural landscape change. Towards this objective, this paper investigates how ABM can contribute to such understanding and promote societal discussion about management options. Empirical evidence informed the ABM in an iterative development process involving in-depth interviews and consultations between and among scientific experts and local farming community members of the municipality of Gera (Lesvos, Greece). The research aimed to illustrate how landscapes are shaped by agent behavior by understanding the heterogeneous land-based decision-making processes of the community, exploring its differing motivational values and attitudes to land management and landscape change. The unravelling of such processes is hypothesized to enable the exploration of alternative futures, leading to an evaluation of how this community and landscape may respond to contrasting scenario storylines with and without consideration of ILIs.

3.2. Methods

3.2.1. Case study area description: Gera, East Lesvos

The research aims were explored within the context of landscape dynamics identified in the former municipality of Gera, located along the eastern coast of the Greek island of Lesvos in the northeastern Aegean. The region's rich cultural heritage is in part preserved in the traditional cultivation of its extensive olive plantations, practiced within what is locally termed a terraced "olive forest". The sheer extent of land area covered by the olive trees, coupled with the low use of artificial inputs, mechanization and the prevalence of a smallholder structure have resulted in a productive landscape highly evocative of a semi-natural system. Olive cultivation in Lesvos plays a role in the delivery of multiple ESs. In comparison to the more intensive systems found elsewhere across the island and the wider Mediterranean, traditional olive plantations in Gera are associated with higher rates of soil retention, enhancement of floral biodiversity and preservation of heritage practices and terraced structures (Beaufoy, 2001; Kizos & Koulouri, 2010). These benefits partly weigh positively in comparison to abandoned plantations, whereby the biodiversity impact is neutral but soil erosion is seen to increase under terrace collapse (Kizos & Koulouri, 2010).

Olive cultivation in the region was effectively a monoculture throughout the greater part of the 18th and 19th centuries (Kizos & Plieninger, n.d.). Recently, marked demographic and landscape transitions have emerged. Gera has witnessed a decline of almost 40% of its population since the 1950s, leaving a consistently negative natural balance and a low percentage of active inhabitants, a trend associated with increased agricultural abandonment gradually resulting in a re-wilding of the region to a forested Mediterranean environment (Bieling & Bürgi, 2014). A declining portion of full-time farmers has left way to part-timers whose household incomes for the large part reside outside of the agricultural sector. While mechanization opportunities are limited because of a sloping and rugged terrain and low accessibility in the uplands, the sector remains highly reliant upon manual labor often fed by seasonal immigration fluxes. Limited alternative employment opportunities are keeping a significant portion of the local population to olive cultivation, yet few successors are willing to uptake land and profession as rural out-migration persists (Kizos et al., 2010).

3.2.2.Overview of methodological approach

The development of an ABM illustrating how the farming community of Gera manages the landscape, now and in the future in the context of macro and micro level changes, adopted a participatory and iterative methodological framework summarized in a 5-step process (**Figure 3.1**), which is elaborated stepwise in **sections 3.2.3 – 3.2.7**.

1. Farmer interviews were undertaken to construct a farmer typology, delineating differing land-based decision-making pathways and informing scenario development (**section 3.2.3.1**)
2. Based on the survey data and spatial data (**section 3.2.3.2**), an initial ABM was constructed (**sections 3.2.4 –3.2.5**)
3. The initial ABM was presented in a workshop (**section 3.2.6**). Concepts, processes and results of the model under different scenarios were discussed with scientific experts in cultural landscapes research and members of the local farming community, with the aim of gathering feedback for subsequent model improvement.
4. Feedback from the workshop was integrated in a refined model, followed by a sensitivity analysis (**section 3.2.7**)
5. Output spatial datasets and the ABM will be made publicly available upon acceptance of the paper (see www.environmentalgeography.nl)

Past research has similarly involved a participatory and iterative ABM development approach, however the participatory component is at times focusing on one aspect of model development only; either scenario development, identification of local problematics, or the discussion of interventions to previously identified problematics (Sylvestre et al., 2013). This study conducted a workshop aimed at addressing four core aspects of ABM to inform model refinement: structural model processes, scenario building, model calibration and visualization of outputs. This approach enabled workshop participants to interpret the model as an object open to critique in all of its constituting aspects, thus increasing its validity and salience.

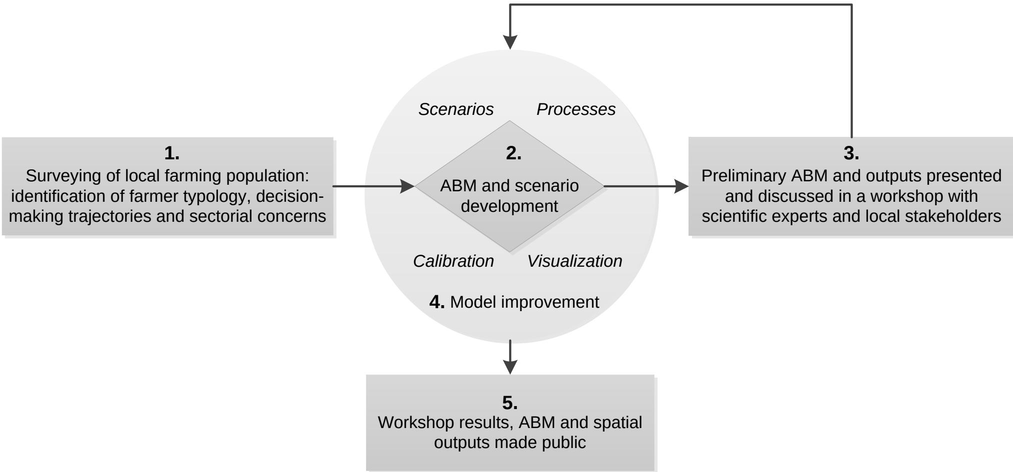

Figure 3.1 – The methodological framework adopted, iterative model development in consultation with local stakeholder and landscape research communities.

3.2.3.Surveying and spatial data

3.2.3.1. Farmer interviews

Interviews with 100 members of the local farming community were undertaken between June and September 2015. The first aim was to use the interviews for the construction of a farmer typology, a widely used approach within ABM (Smajgl et al., 2011) providing type-based probabilities of occurrence for a set of attributes (**Table 3.1**). The typology was constructed via hierarchical cluster analysis (see Zagaria et al. (2018)) and revealed three farmer types: active part-timers, professionals and detached farmers (described in **Table 3.2**). A discriminant function analysis illustrated how two functions significantly discriminated the three identified farmer types, respectively accounting for 89.1% and 18.1% of the variance with canonical correlations of 0.906 and 0.708 (Zagaria et al., 2018). As a second objective, the interviews were used to elicit the future perspectives of the farmers. The interviews revealed nearly 70% of farmers expected disinvestments within the coming decade. This was most widely foreseen by the active part-timers, despite their reliance upon alternative sources of income, emphasizing the importance of sectorial profitability. A similarly large share of farmers expressed continuing the current farming system as the most viable course of action, while participation in social cooperatives as well as in agricultural trainings remains limited.

Table 3.1 – Overview of farmer agent attributes whose values were set empirically according to their probability of occurrence within the constructed farmer typology.

Attribute	Description	Value measure
Farmer type	A farmer belongs to one of three types (active part-timer, detached farmer or professional); typology created by means of cluster analysis from interviews with a sample of the local farming community.	1 = Active part-timer 2 = Detached 3 = Professional
Culturally driven	The farmer has inherited land, expressed a desire to maintain it in the family and a refusal to sell	Y / N
Imitator	The farmer bases farmland decisions on the experiences of their neighbors	Y / N
Social cooperative member	The farmer is a member of an existing social cooperative; these farmers represent the initial adherent farmers to ILIs if activated in model run	Y / N
Higher level of schooling	The farmer has obtained high school level education	Y / N
Makes use of consultancies	The farmer makes use of external sources of information when making decisions on his farming system (cooperatives, formal consultancies, research organizations, internet sources)	Y / N
Has successor	The farmer has a willing successor	Y / N
Hires labor	The farmer hires labor	Y / N
Age: 18 – 34 years	The farmer belongs to the young age group	Y / N
Age: 35 – 49 years	The farmer belongs to the younger middle-aged group	Y / N
Age: 50 – 64 years	The farmer belongs to the older middle-aged group	Y / N
Age: > 64 years	The farmer is at or above retirement age	Y / N
Management intensity	Intensity with which the farmer manages the farm, assumed to be equal amongst all plots owned by the farmer. This composite indicator is a measure of family labor, use of fertilizers, pesticides or herbicides, pruning intensity, stone wall/terrace maintenance, mechanization, tree density and irrigation.	1 = Low intensity 2 = Medium intensity 3 = High intensity

Number of plots	Number of plots belonging to a farmer	1 – 11
Farm size	Total farm size (sum of all plots owned by the farmer)	0.1 – 20 ha

Table 3.2 – Defining attributes of the three farmer types obtained in the cluster analysis listed alongside the (%) distribution of farmers across the typology (Zagaria et al., 2018).

Farmer type	**Active part-timers** (27%)	**Professional farmers** (24%)	**Detached farmers** (49%)
Defining attributes	Culturally driven	Culturally driven	Lowest share of culturally driven farmers
	Extensive agricultural knowledge	Extensive agricultural knowledge	Low formal agricultural training
	Makes use of external sources of knowledge (consultations)	Makes use of external sources of knowledge (consultations)	Low use of external sources of knowledge (consultations)
	Significant non-agricultural incomes	Full-time farmers	Mix of full-time and part-time farmers
	High level of schooling	High level of schooling	High level of schooling mostly not obtained
	Low-intensity farming	Larger and more intensively managed farms	Low-intensity farming
	Mixed age group	Highest share of farmers in younger age groups	Dominated by ageing farmers
	Believe the future agrarian sector will be reliant upon pluri-active farmers	Fewest share of pessimists regarding the future agrarian sector	Largest share of pessimists regarding the future agrarian local sector
	Few are social cooperative members	Highest share of social cooperative members	Lowest share of social cooperative members

3.2.3.2. Derivation of spatial datasets

Farmer interviews informed local spatial dynamics by geo-tagging the location of farming plots belonging to the interviewees. The importance of accessibility of farming plots was emphasized, as farmers stated de-intensification and abandonment to be more likely in poorly accessible locations. A plot accessibility layer was therefore created, defined by proximity to the road network. The accessibility map was used as a proxy for the computation of a farmer's annual transport costs and included in a land suitability layer used for plot selection during the model's computation of annual land transactions. The suitability layer was generated by means of random forest regression (details in SI) making use of the recorded plot locations and aspect, elevation, slope, geology, visibility, distance to the sea, accessibility and distance to settlements. These variables were identified as influential determinants to land suitability (or value) by both experts in local landscape change dynamics and interview data.

The distribution of plots belonging to the interviewed sample across the land suitability layer was used to create a cadastral data layer. The total farming population was set to 1500 according to 2011 census data (ELSTAT, 2011), while the distribution of farmers over the types and the number of plots per farm were set according to the farmer survey (details in the SI). Initial plot size distribution was designed to mirror the plot size *ratios* (rather than true plot size area) identified between farmer types. Here, professional farmers own plots on average larger than the remainder two farmer types, and active part-timers the smallest.

3.2.4.Model design

The model is built upon an understanding that dynamics surrounding agricultural abandonment in the heritage olive-dominated landscapes of Gera are subject to aggregate complexity stemming from the interactions of system components at the micro-level and behavioral, temporal and spatial dimensions (Janssen, 2003; Manson, 2005; Verburg, 2006). We conceptually framed the system as being dependent on two constituting entities: (1) farmer agents, i.e. decision makers defined by behavioral attributes, and (2) multi-level drivers, based on the premise that their aggregate behavior and interactions determine landscape and demographic transitions.

3.2.4.1. Behavioral attributes of farmer agents

As revealed by the survey, actors are heterogeneous in their behavioral attributes, hereby differentiated between managerial strategy (farming intensity) and three decision-making components (goals, past experiences and interactions). These attributes are modelled through the attributes of the farmer agents, defined and operating as follows:

1. *Goals* are represented by a farmer having either a cultural or a non-cultural drive (**Table 3.1**). The model assumes all farmers seek to maximize their annual revenues by purchasing the most productive land plots (if opting to buy). However, culturally driven farmers refuse to sell their land if opting to scale-down and choose to abandon instead, thus disregarding potential financial gains in this decision-making aspect. Farmers are considered boundedly rational as full optimization of their goals rarely occurs. This is a result of an agents' limited cognition and information, representing the more partial strategies occurring in the area (Manson, 2006; Parker et al., 2003).
2. Agricultural knowledge was assumed to be dependent on a farmer's (1) *past experiences* and (2) *interactions* via imitation and consultation. Specifically:

   (i) All farmers account for past experiences by favoring actions they have previously undertaken (see also Valbuena et al. (2010)).

   (ii) Imitating farmers are assumed to actively and more deliberately undertake more interaction with other agents than non-imitating farmers in order to increase their knowledge base (social learning (Brown et al., 2017)). Because farmers own plots scattered across the region, imitation is not based on the actions and attributes of neighbors but rather on those of the predominant farmer type in the region that given year. Imitation affects farmers' decision-making regarding land-system change (whether scale or intensity based) and their decision to adhere to ILIs by altering the farmer's subjective norms. Subjective norms illustrate the influential and "perceived level of approval or disapproval by important others" (Kaufmann et al., 2009). Alongside a farmer's attitude and perceived behavioral control, subjective norms hereby shape the diffusion of ILIs utilizing concepts from the Theory of Planned Behavior.

   (iii) Consulting farmers are similarly assumed to have access to additional knowledge sources; the model thus sees consulting farmers having a higher probability to adhere to ILIs because of altered perceived behavioral control, representing a farmer's ability to perform a certain behavior.

3. A farmer's *management strategy* represents the intensity of farm inputs used, including hired labor. Farmer interviews revealed significantly higher intensity levels among professional farmers and social cooperative members. In the model, when farmers join ILIs or switch to a professional type, they thus alter their management behavior to higher intensity. Switching to higher annual intensity levels assumes higher yields but also higher annual costs to farmers.

3.2.4.2. Attributes of multi-level drivers

The drivers of change incorporated within the model are "multi-level" or multi-scale, as they account for both external (macro) drivers and locally based ILIs. The state of macro drivers is set according to scenario conditions, while locally based ILIs can be activated or de-activated during a model run.

- Macro drivers of change are based on de Graaff, Duran Zuazo, Jones, & Fleskens (2008), having modeled sloping and mountainous olive production systems of the Mediterranean under a range of socio-economic development scenarios. Their study identified primary influential factors to the future development of olive production systems to include *labor wages*, *subsidization policy* and the market *price of olive oil*. We adopted two of the four scenario storylines developed by de Graaff et al. (2008), notably the "Bright" and "Doom" scenarios, which simulate contrasting changes to the three attributes. This representation mirrored the concerns identified in our case study area, closely linking sectorial profitability and availability of labor to the maintained cultivation of olive plantations.
- ILIs were not modelled as separate "agents" but rather manifested themselves by directly inducing changes to the behavioral attributes of adherent farmers. Starting typology-based probability of membership to ILIs was based on farmer interviews investigating whether farmers were members of presently existing social cooperatives (more prominent amongst professional farmers, **Table 3.2**). Like a farmer's cultural motivations, membership to ILIs is re-

considered by successor farmers and not an inherited attribute (**Figure 3.4**). If ILIs are activated in the model run, each farmer that is not already a member will consider joining. Their diffusion is enhanced by: imitating farmers responding to an increasing portion of farmers in the region having already adhered to the initiatives, the inquiring farmer's cultural drive, schooling level and use of external consultations (**Figure 3**). Joining an ILI in turn increases (or maintains) a farmer's *management intensity* to the highest level, sets (or maintains) a farmer's goal to *cultural*, introduces (or maintains) the farmer to external *consultancies* and increases the probability that the farmer will have a willing *successor* (supporting literature in García-Martín et al. (2016); Sottomayor, Tranter, & Leonardo Costa (2011)).

3.2.5. Model imlementation and scheduling

An outline of model processes undertaken in each yearly run is illustrated in **Figure 3.2**, describing the scheduling of the farmer decision-making processes, the points of influence of ILIs and macro-level drivers and instances where decisions directly affecting landscape changes may occur. The model was developed in the open source environment NetLogo version 5.3.1 (Wilensky, 1999), making use of the GIS extension. The processes outlined are those set in place following a model refinement phase informed by a workshop with experts in cultural landscape change and members of the local farming community (**section 3.2.7**). A comprehensive overview according to the Overview, Design Concepts, Details + Decisions Protocol (Grimm et al., 2010; Müller et al., 2013) and a list of attributes of the model's entities are outlined in the SI.

3.2.5.1. Decision-making processes and behavioral transformations

Both behavioral attributes (**section 3.2.4.1**) and non-behavioral attributes of farmers (e.g. age, level of schooling) define the three types of decisions faced by farmers in a yearly model run, notably: (1) land-based decisions, (2) type-switches/behavioral transformations and (3) adherence to ILIs (respectively steps 2, 5 and 6 of **Figure 3.2**):

- *Land-based decisions*: Farmers annually decide to expand or shrink their farm following the computation of annual wealth. If farmers have enough wealth and own below the maximum manageable farmland area, they will consider expansion. A decision to expand relates to behavioral attributes of past experiences and inter-agent interaction; farmers are assumed path-dependent and more likely to expand if imitators and in a context of prevailing professionalism. Additionally, younger farmers are more likely to expand (widely expressed as an influential factor throughout the stakeholder workshop (**section 3.3.1**) and in part related to more opportunities in terms of subsidies and other financial supporting schemes). Decisions regarding shrinking of farm are considered if a farmer does not meet the required minimum wealth for purchase. This decision is dependent upon a farmer's cultural drive (goals), but also their past profits (or lack-thereof) and level of schooling. Younger farmers with a higher level of schooling, having witnessed declining profits are assumed as more likely to opt for shrinking of system as part of a transition to alternative employment (see also Acosta et al. (2014)), while farmers having recently witnessed increasing profits do not consider scaling down. The same decision-making process is run for cultural and non-cultural farmers, yet when opting to scale down cultural farmers will choose to abandon rather than sell. The final probability value to sell is set to always be higher than that to abandon, as abandonment is assumed as a more reluctant decision taken by farmers. **Figure 3.3** illustrates how these specific attributes hold equal weight in determining the probability of a farmer undertaking each of these actions.
- *Behavioral transformations*: Behavioral transformations are represented by farmers undergoing type-switches. Decisions to undergo a type-switch follow the expansion or shrinkage of the farm system, and are in part dependent on such past-actions and profits. If a professional farmer is making losses and has lost substantial farmland, they may consider de-intensification of their farm and a switch to an active part-timer type. Culturally driven farmers are also more likely to transition

away from the detached type and vice-versa. Type-switches are age dependent, under the assumption that farmers above retirement age will not undergo type-switches unless they are professional farmers, in which case they will switch to the active part-timer type upon retirement. The probability of a farmer undergoing a type-switch is determined by all of the dependent attributes occurring, thus differing from decisions illustrated in **Figure 3.3** whose probabilities are determined based on the summated occurrence of attributes. **Figure 3.4(a)** illustrates the immediate feedbacks surrounding such behavioral transformations. Undergoing a type-switch only alters a farmer's behavioral management strategy, not affecting the decision-making attributes of the farmer. Key to understanding the implications of such a transformation is the consideration of successors and inheritance of attributes (**Figure 3.4(b)**). Successor farmers do not inherit but reconsider their goals, or cultural motives, depending on their inherited type. The model thus allows for an investigation of changing behavior past the present generation of farmers.

- *Adherence to ILIs (if activated in model run)*: Following land transactions and potential switch in farmer type, farmers consider joining ILIs. This decision influences both aspects of behavior, driving farmers towards more culturally oriented goals and promoting interactions for knowledge transfer. By directly influencing the decision-making attributes of agent behavior, adhering to ILIs thus enhances likelihood of undergoing a type-switch in subsequent time steps (**Figure 3.4(a)**).

3.2.5.2. Landscape changes

These dynamics and interactions thus hold varying implications for landscape change. Changes in management strategy imply a direct intensification or de-intensification of the current farming system. This changes a farmer's annual costs and thus may additionally influence scale-based decision-making in subsequent time steps. A single plot is assigned to a decision regarding the purchase or selling/abandonment of land, selected according to whether it has the highest or lowest land suitability value respectively. Following a period of abandonment of 5 years, fields witness a land-cover transition to wooded grassland and shrub, after an additional period of abandonment of 15 years the fields are considered forested (Koulouri & Giourga, 2007). As land undergoes land-cover changes to shrub or forest the land suitability value of land decreases, in turn decreasing the likelihood of abandoned fields being purchased. If a farmer buys a plot that was previously abandoned, the farmer undergoes a one-off land conversion cost and the plot increases in land suitability value.

3.2.5.3. Scenarios

This study draws conclusions based on the results of four simulations. The outcomes of Doom and Bright scenarios, setting contrasting annual rates of change for the values of the three macro drivers, are evaluated individually with and without the implementation of ILIs. The contrasting annual rates of change in olive oil prices, labor wages and subsidy support under Bright and Doom scenarios are outlined in **Table 3.3**.

Table 3.3 – Macro drivers of change under the two contrasting "Bright" and "Doom" scenario storylines; values represent annual rates of change (%).

	Annual rates of change (%)		Change over simulation period of 25 years	
Attribute	**Bright**	**Doom**	**Bright**	**Doom**
Olive oil prices	2	0	50% increase	No change
Labor wages	0	2	No change	50% increase
Subsidies	1	-4	25% increase	Phased-out entirely

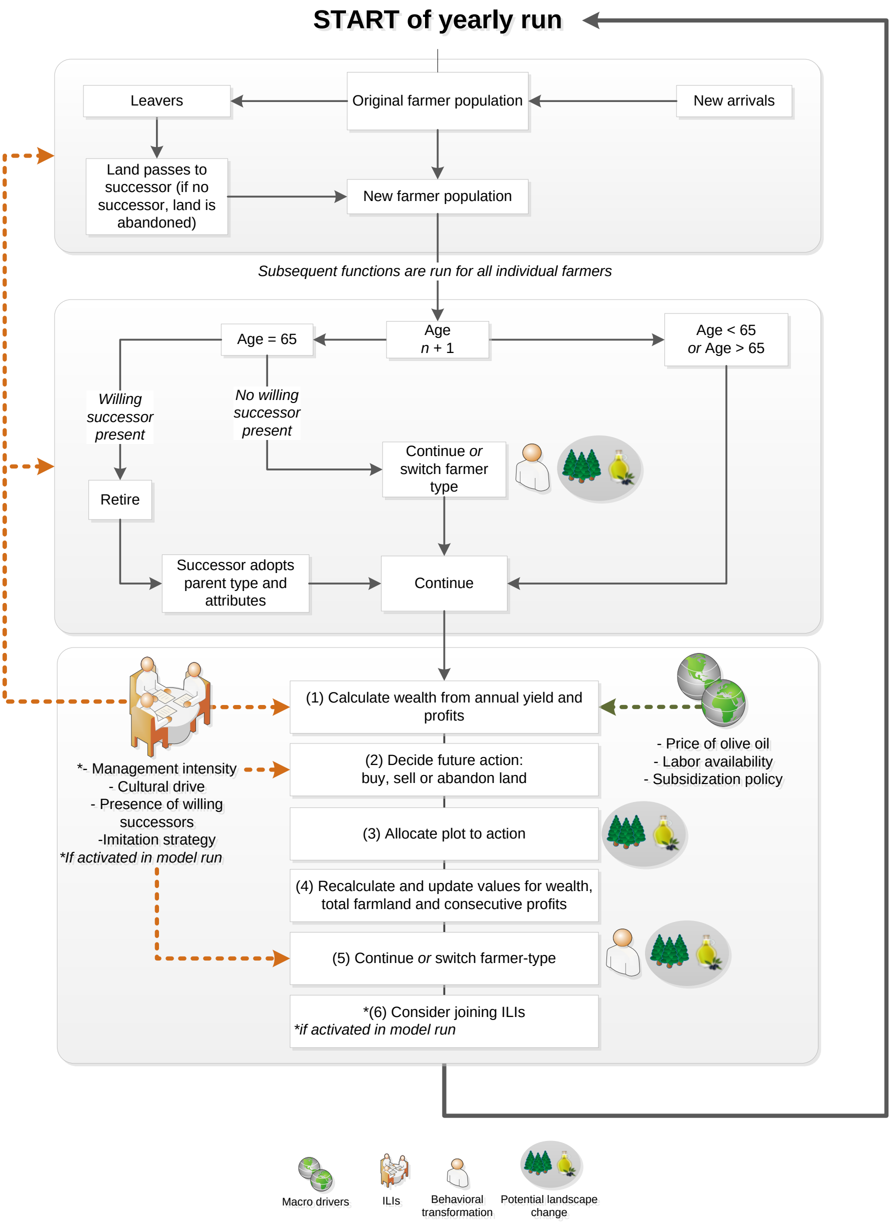

Figure 3.2 – Overview of yearly model run, outlining points of influence of changing macro drivers and implemented ILIs.

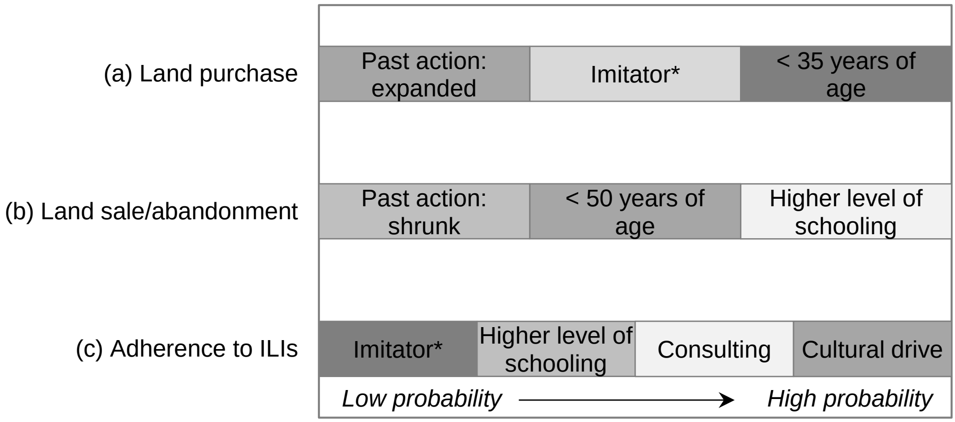

Figure 3.3 – Establishing probabilities for farmer decision-making regarding (a) expansion or (b) shrinking of farming system and (c) adherence to ILIs. The occurrence of each listed farmer attribute increases the probability of the decision taking place by an equal amount. *In a prevailing professional farmer type context, imitating farmers favor purchase of land. In a year where detached or active part-timers are the prevalent type, an imitator attribute disfavors purchase while a non-imitator attribute would encourage it. Regarding adherence to ILIs, imitating farmers have a higher probability of adherence regardless of the prevalent farmer type.

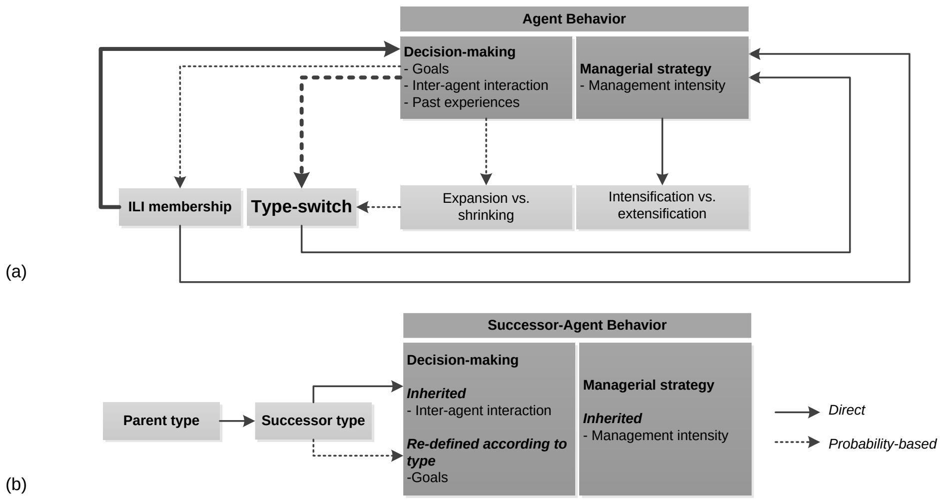

Figure 3.4 – (a) Feedbacks between type-switches, ILI membership and behavioral attributes and consequential effects on landscape change; emphasis is placed on the

role of ILIs in altering decision-making attributes and enhancing behavioral transformations via type-switches; (b) Inherited and re-defined behavioral attributes of successor farmers to be considered in the understanding of implications of behavioral transformations for the coming generation of farmers.

3.2.6.Stakeholder workshop: model validation and refinement

A workshop was held with cultural landscape experts and members of the local farming community to validate and refine the preliminary model. 38 people participated in the workshop: 23 cultural landscape experts and 15 representatives of the local farming sector. The workshop took place on April 21, 2016 in Pappados, Gera, and lasted 2 hours, making use of breakout groups, individual anonymous questionnaires and open discussions. This diversity in eliciting approaches was adopted to maximize input from participants.

The workshop began with an explanation of the model, its input data sources, conceptual framework, development process and procedures resulting in diverging scenarios. The researchers stressed the model was a tool that, despite having a strong empirical component, necessitated additional critical insight from both the local farming and external landscape experts, asking the participants for their help in improving the ABM by discussing (1) its modelled procedures, (2) scenarios, (3) the magnitude of driving and non-driving variables and (4) the visualization of outputs.

Following explanations, local community members were split into three groups each discussing one of the three initially modelled scenarios, while cultural landscape experts brainstormed and discussed all scenarios as a group. The groups were presented with their respective scenario for discussion on an A2 poster and handouts illustrating demographic and landscape changes and were handed pens and post-its with which to transcribe their feedback. The two communities were subsequently asked to fill in separate questionnaires (in SI). These aimed to validate or challenge the modelled processes and concepts while also including a feedback section on the workshop process. An open discussion amongst local community members followed, addressing future challenges and opportunities associated with the local agricultural sector.

Following Johnson (2015), the workshop aimed to address many drivers of change, while understanding that their inclusion within a "final" model may not be desirable or possible. This approach was favored as to focus discussion on challenging model assumptions and to avoid misrepresentations or misunderstandings in the final outputs. Therefore, the scenarios presented in the workshop differed from those outlined in **sections 3.2.4.2/3.2.5.3**, primarily by presenting causal relationships and feedbacks between ILIs and macro-level drivers. Workshop findings resulted in alterations to a final model following an iterative process of qualitative evidence gathering and analysis similar to that of Polhill, Sutherland, & Gotts (2010). The results thus present summarized (primarily qualitative) evidence from the workshop, illustrating how and why findings were or were not integrated within a refined model.

3.2.7.Sensitivity analysis

As the model includes stochastic processes, it was necessary to establish a number of replications from which to average model output results. Using baseline values for all variables, the coefficient of variation was calculated for 13 model output variables, under each scenario, for 30 runs (Lorscheid et al., 2012). This led to the selection of 20 iterations for determining final average-based output values. Sensitivity analysis was subsequently undertaken using a one parameter at a time (OAT) analysis. Despite the limitations of this method, this approach was deemed appropriate due to its simplicity providing sufficient and fast insight as well as enhanced communication potential.

Similarly to Schouten, Verwaart, & Heijman (2014), minimal and maximal value ranges to the variables altered by sensitivity analysis were set around the pre-defined base value to evaluate as part of the sensitivity analysis. Description of the analysis process, variables used and value ranges tested are found in the SI. Model sensitivity to the parameters altered by macro conditions or ILI implementation was not assessed by testing maximum and minimum value ranges as these parameters were either binary or set upon specific values whose alteration would not be possible, as it would disrupt modelled processes dependent upon specific ratios related to these parameters. Their analysis was therefore undertaken by running the model with and without any change occurring to each of these parameters individually.

3.3. Results

3.3.1.The stakeholder workshop

3.3.1.1. Feedback on model structure and validity

The local farming community largely confirmed the processes integrated within the preliminary model. Discussions showed agreement with the farmer typology and the variables used for mapping land suitability, including the critical role field accessibility plays in abandonment. Participants stressed the importance of sector profitability for sustaining agriculture and heritage in the future, ("[economic] motivation is needed so that the number of producers will increase and become more active") and they agreed a scenario portraying gradual removal in subsidies is likely to result in increased abandonment. There was general consensus on the importance of current olive oil prices ("the price of olive oil is low at the moment, meaning no profits, no labor hiring and no development"), which was also deemed the most influential factor in the emergence or success of ILIs. Subsidies were deemed least influential (**Table 3.4**).

Management intensity was confirmed as key attribute in determining yields; age and external consultations were seen as key attributes for scale expansion and age and level of schooling for decisions to scale down. Few participants did not give a weight or provided an "other" variable in the weighing exercises. This indicates the variables in the preliminary model to be largely representative (**Table 3.4**). Estimates on the number of newcomer farmers and proportion of farmers to join ILIs did not reveal significant trends. Landscape experts characterized ILIs as influential to societal change, drawing upon concepts of existing community networks and knowledge transfer and exchange. The importance of sectorial cooperation was stressed in the mentioning of a necessity for better legislative frameworks, political support, subsidized local markets and development of tourism.

Table 3.4 – Average weight scores attributed to influential factors comprising modelled processes by the local community in the weighting exercise of the questionnaire. Also stated are the average number of "other" factors and NA scores provided by respondents per weighting exercise.

Model process	Influential factors Highly rated	Average score	Lowly rated	Average score
Emergence/success of ILIS	Price of olive oil	4.6 / 5	Subsidies	2.8 / 5
	Accessibility	4.0 / 5	Labor wages	3.1 / 5
Annual yield	Management intensity	2.8 / 3	Slope	2.1 / 3
Scale expansion	Age	2.6 / 3	Past actions	2.2 / 3
	Use of external consultations	2.6 / 3		
Scale decline	Age	3.6 / 4	Past actions	2.7 / 4
	Education	3.3 / 4	Cultural drive	3.0 / 4
	"Other" answers provided per weighting exercise	1 / 14	**NA scores provided to variables per weighting exercise**	4 / 14

Breakout groups discussed nuances to the straightforward causal relationships in the preliminary model. **Table 3.5** presents a summary of the feedback obtained on the preliminary model presented, alongside an explanation of how and why comments were or were not integrated in a refined model version. Half of the cultural landscape experts were "unsure" the macro-level drivers specified (including land availability and accessibility in this preliminary model version) would determine the emergence or success of ILIs in the region, stating that the mentioned drivers represented a predominantly economic, rather than cultural or comprehensive, perspective. Similarly, 47% disagreed ILIs would not emerge in a scenario illustrating agricultural liberalization; a lack of political willingness and action to tackle local abandonment could "push" the emergence of grassroots initiatives to address these issues.

Additional statements expressed by both communities supported post-workshop model alteration to two contrasting scenarios. Locals did not see the continuation of current trends in a “Business as Usual” scenario as realistic as the present situation is largely deemed unsustainable. They stated “no-one can buy land these days”, “due to economic crisis, farmers get the most of their available land” and “most farmers of the region cannot afford investments”. Locals additionally felt the scenarios resulted in unexpectedly insufficient diversity in landscape change. An absence of middle grounds was palpable also in the final open discussion. While some members of the local farming community advocated for stronger mobilization for heritage protection and conservation, making use of tourism resources, other farmers opposed this view and called for re-grounding focus on enhancing productivity of olive plantations as this is the only way to secure profits to the sector (**Table 3.5**).

These comments resulted in a refined ABM that aimed towards a more abstract representation of the local dynamics identified, in order to better reflect uncertainty expressed by workshop participants and increase the credibility of the ABM through a more transparent presentation of its explorative nature. For example, the scenarios of the refined ABM see ILIs not as emergent to a set of conditions but as imposed by the model user in different, comparative simulations. Abstraction was furthermore introduced due to the uncertainty expressed by local participants regarding outcomes of potential feedbacks and interactions amongst drivers (**Table 3.5**). Participants suggested a collapse of subsidies could lead to widespread abandonment but may also feedback to new farmers because of higher land availability. Other participants stated they expected further declines in olive oil prices due to the involvement of countries with lower labor wages in the market. Yet participants recognized these processes as unpredictable, depending, for example, on migration fluxes. This exemplifies the ease and accuracy with which workshop participants grasped the ABM processes, and, importantly, the potential of the method in facilitating discussion on the multi-faceted complexities inherent to local landscape change.

The consideration of additional processes, feedbacks or scenarios was purposely brought into workshop discussion in order to increase legitimacy, salience and credibility of both the modelling process and the model itself. The ABM constructed is an explorative investigation to the socio-cultural behavioral transformations pertinent to a cultural landscape. The scope for pursuing additional detail in biophysical and economic representations is thus limited. Sun et al. (2016) elaborate on concepts of "appropriate" complexity (relating to model behavior) and complicatedness (relating to model structure) in ABMs of human-environment system. Some processes were excluded from our final model to refrain from reaching a level of complicatedness undesirable within ABMs and paradoxically introducing further uncertainty via the assumptive creation of additional causal relationships (Axelrod, 1997; Le et al., 2012) (**Table 3.5**). The consideration of these identified, discussed but omitted processes enables the framing of a context in which final model results are to be interpreted, while identifying the strengths and limitations of empirically co-constructed ABMs (see Discussion).

Table 3.5 – Synthesis of statements by cultural landscape experts (C) and local farming communities (L) that either explicitly stated feedback on model improvement or elicited model improvement while emerging from wider discussions about present sectorial concerns throughout the workshop. Rationale behind choice of integration or non-integration in a refined model is specified for each statement. The three scenarios discussed at the workshop differed from the final scenarios adopted; these were originally termed: (1) Business as Usual; (2) Conservation of the Traditional Landscape; (3) Agricultural Liberalization.

	Statements (C = cultural landscape experts, L = local community)	Integrated ?	Modification	Rationale
Processes	(L) Divergent views: plot sale or purchase based solely upon land suitability vs. emotional attachments to plots irrespective of their suitability values	N	-	Low profitability of sector identified as a limiting factor for all farmer types, translated to all farmers choosing to maintain or purchase most productive plots; difficulty of linking emotional bonds with specific plots to spatial attributes.
	(L) Processes of climate change, political instability and financial crisis would alter the modelled process by increased desertification, spread of disease, changes to taxes, agricultural reforms and tourism influences	N	-	Avoid over-complicatedness via integration of detailed biophysical (yield changes, crop pests, desertification), cross-sectorial and economic (housing, labor markets) modelling deemed beyond scope of an ABM emphasizing socio-cultural processes. Participants rejected assumptions behind the direct feedbacks between macro-drivers and emerging ILIs. The inclusion of some of these processes without further empirical investigation is likely to have similarly increased undesired model uncertainty retracting from model credibility. Participants also stated politics and migration dynamics are partly reflected in subsidies and labor wages,
	(C) Additional factors are important and may alter the model processes: gender roles, the wider job and housing markets, climate change, energy availability and price, migration, subsidized agricultural technologies	N	-	

(L) Additional feedbacks are important and may alter the model processes: more land availability, altered wages from new, competitive markets	N	-	variables included in the final ABM and whose effect can therefore indirectly be explored in the model and sensitivity analysis. Some of the processes mentioned by the (C) group (gender role, energy availability, agricultural technologies) were not identified as significant influential factors within the initial farmer surveys, and were excluded from the final model on this basis
(L & C) Purchase of abandoned plots is possible but difficult and requiring high costs to purchasing farmers	Y	Rendered abandoned plots available for sale in all scenarios. Included conversion costs to farmers purchasing previously abandoned plots	More accurate representation of occurring processes to increase validity and credibility of model
(L) Road construction is very difficult in the region	Y	Changes to road network and plot accessibility do not occur under any scenario	Limit amount of macro drivers, translate changes to accessibility and demographics to wage rates only; closer alignment with de Graaff et al. (2008); limit complicatedness
(C) Links between state of macro drivers and emergence of ILIs cannot be assumed linearly	Y	Macro drivers and ILIs are decoupled; ILIs are not seen as emergent but imposed under two contrasting scenarios with divergent properties of macro drivers	Assumption of direct causal linkages between ILIs and macro drivers rejected by participants at workshop; limit complicatedness; allow for a more direct comparison of the effects of the two drivers
(L) Other strategies identified: use of non-native olive varieties and sale of olive tree wood to guarantee small but safe profit	N	-	Diversification of income sources was more abstractly captured in the behavioral attributes of the active part-timer and disengaged farmer types, without the explicit inclusion of additional income in the model and thus not differentiating between on or off-farm income sources (wood sale, crop switch, agro-tourism, etc.).
(L) Young people reluctant to get involved in sector	Y	Introduced new generation as an attribute and monitor plot in the	Allow for assessment of landscape and behavioral transformations beyond the present generation of farmers; provide an analysis of

			model interface; calibration of probability of succession	generational change; more accurate representation of occurring processes to increase validity of model
Calibration	(L) At present very few farmers are buying or are able to make investments of any kind	Y	Calibration of probability of land expansion by farmers	Increase model validity, credibility
	(L) Management intensity is the most important factor determining yield. Highest annual costs attributed to hired labor, lowest to transport	Y	Weighting of yield function to account for importance of management intensity over slope	Increase model validity, credibility
	(L) Higher importance of age and education than past actions and cultural drive when choosing to scale-down; high influence of age and external consultations in comparison to past actions when expanding; high importance of olive oil prices and low influence of agricultural subsidies in the emergence of ILIs	N	-	Factors remain equally important in decision-making due to controversial use of averages for setting equal weights across a heterogeneous farming population
Scenarios	(C) Uncertainty was expressed with regards to whether the scenarios and model captured the local situation in a realistic and credible manner	Y	Two new scenarios implemented illustrating divergent properties in macro drivers	More accurate representation of occurring processes as expressed throughout workshop to increase validity of model
	(C) Alternative scenarios which would be important to consider: climate change, permanent residence of migrants, agricultural education, role of migrations in tourism industry, subsistence	N	-	Avoid inclusion of assumptive feedbacks (in lack of empirical data) likely to undermine model credibility. The final scenarios sought to more abstractly represent divergent storylines (in response to participant feedback) favoring and disfavoring abandonment by altering the state of the final macro-variables chosen. These do

farming, political and financial collapse			not directly refer to the scenario names listed here yet are able to indirectly represent some of them: e.g. agricultural education (via ILIs), permanent residence of migrants (increased newcomers, changing wages), etc.
(C) Agricultural liberalization is too ambiguous a term to be utilized as a scenario description	Y	New scenarios more abstractly titled Bright and Doom	Two deliberately diverging storylines favoring and disfavoring abandonment assume no linkages between macro drivers themselves; limit complicatedness
(L) “Business as Usual” scenario not realistic, the current situation is not sustainable	Y	Removal of BAU scenario, implementation of two contrasting scenarios only	Two deliberately diverging storylines favoring and disfavoring abandonment assume no linkages between macro drivers themselves; shift focus to explore and discuss consequences of “what if’s?” and remove assumptive linkages
(L) Scenario results not very “extreme”	Y	Two new scenarios implemented illustrating divergent properties in macro drivers	Two deliberately diverging storylines favoring and disfavoring abandonment assume no linkages between macro drivers themselves; shift focus to explore and discuss consequences of “what if’s?” and remove assumptive linkages
(L) Divergent views: return to the more productive functions of olive cultivation vs. pursuit of heritage conservation as part of tourism-oriented initiatives	N	-	Interactions with tourism industry, both in terms of additional sources of income and land use transitions deliberately not included in model as to limit complicatedness by the analysis of olive-cultivation transitions only. These views are however manifested in decision-making regarding adherence to ILIs (assumed to stem from desire for heritage conservation in the cultivated olive landscape)
(C) Incorrect to assume ILIs would not emerge in a scenario forecasting agricultural liberalization	Y	Macro drivers and ILIs are decoupled; ILIs are not seen as emergent but imposed under two contrasting scenarios with divergent properties of macro drivers	Assumption of direct causal linkages between ILIs and macro drivers rejected by participants at workshop; limit complicatedness; allow for comparison of two drivers

Visualization	(C) Clearer visualization of land use changes and actor types needed	Y	New maps depicting plot ownership according to the farmer typology; simplified background and land use classification	Increase readability and communication of results

3.3.1.2. Stakeholder evaluation of the workshop process

Over 90% of cultural landscape experts agreed the workshop allowed them to both share and acquire new knowledge. Two-thirds agreed the modeled simulations represented a helpful tool in discussing alternative futures. There was stronger consensus within the local farming community about the utility of the workshop and ease of understanding of modelled processes. Detailed results of the stakeholder evaluation are in the SI.

3.3.2.ABM simulations

All four scenarios envisage a decline in farming population numbers and increase in the extent of abandonment across Gera over the upcoming 25 years. The smallest changes occur in the Bright scenario with implementation of ILIs. Here, a 13% decrease in farming population and abandonment of an additional 10% of fields was expected (**Table 3.6**). Only the "Bright + ILIs" scenario is able to demonstrate a reversal in abandonment trends within the simulated period (**Figure 3.6a**), beginning 17 years into the simulation and associated with a recovery in farmer numbers (**Figure 3.8a**). ILI implementation under Bright conditions reduces population decline and extent of abandonment by 18% when compared to the "Bright – ILIs" scenario. While at least a stabilization of abandonment rates seems to occur within both Bright scenarios, trends under Doom conditions suggest a collapse of the farming population irrespective of ILI implementation; both storylines foresee a decline in farming population by 58% and abandonment extent almost reaching 80%.

In scenarios where ILIs are implemented more than 50% of farmers adhere to the initiatives. ILI implementation is crucial to the intensification of land systems and promotion of new generation farmers under both Bright and Doom conditions (increases of approximately 65 and 30% respectively, **Table 3.6**). The proportion of new generation farmers is equal in both Bright and Doom scenarios, despite numbers of farmers varying considerably, due to the passing of the land to new generation farmers when the present generation reaches retirement age. De-intensification is much less prevalent under all simulations, although highest in the "Doom – ILIs" scenario.

Table 3.6 – Model results illustrating the extent of landscape and demographic changes following a 25 year simulation under two contrasting Doom and Bright scenarios, with and without the implementation of ILIs. Values are averages of the final yearly time-steps from 20 complete model runs. *Starting conditions: abandoned fields (32%), ILI members (11%).

Scenario	% Change in farmer population	% New generation farmers	% ILI members*	% Abandoned fields*	De-intensified fields (% of cultivated)	Intensified fields (% of cultivated)
Bright + ILIs	-13	71	74	42	3	82
Bright - ILIs	-31	41	7	60	8	18
Doom + ILIs	-58	71	63	79	5	81
Doom - ILIs	-58	41	6	78	11	14

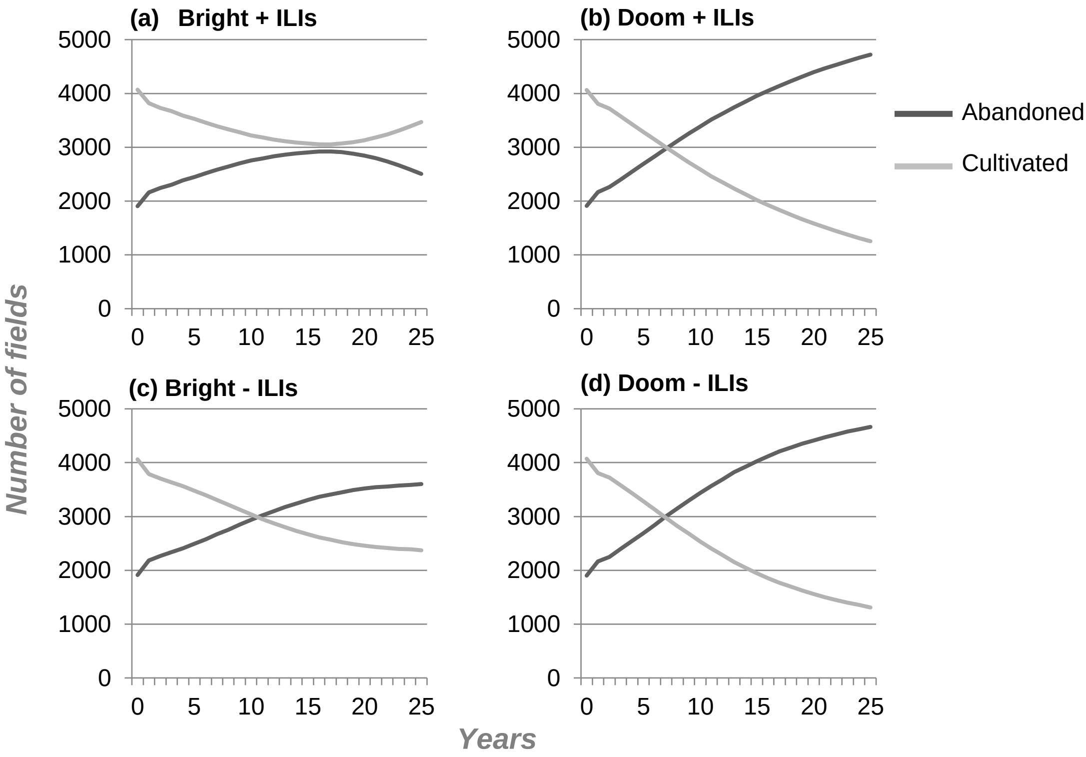

Figure 3.6 – Number of abandoned and cultivated fields throughout a 25 year simulation under two contrasting Doom and Bright scenarios, with and without implementation of ILIs. Values are averages from 20 complete model runs.

These changes are associated with transitions occurring between the different farmer types (**Figure 3.8**, **Figure 3.9**). Favorable changes to macro drivers alone do not sufficiently trigger behavioral transformations able to shift the prevalent worldview; as can be seen in the "Bright – ILIs" scenario whereby the predominant farmer remains detached. The trend is less pronounced then in the "Doom – ILIs" scenario, where detached farmers represent 61% of the farming population compared to 37% (**Figure 3.9**). Implementation of ILIs sees a shift in the predominant farmer type from detached farmer to professional irrespective of the main scenario storyline. Nevertheless. this behavioral transition does not suffice to halt abandonment. While ILIs favor active part-timers over detached farmers under Bright conditions, the opposite is true under Doom. The "Doom + ILIs" scenario most closely resembles the present distribution of farmer types, enhancing the prevalence of detached farmers. The two most contrasting scenario storylines ("Bright + ILIs" vs. "Doom – ILIs") demonstrate a polarization of professional and detached farmer types prevailing across the region.

Under all four scenarios the most frequent type switches occur from the active part-timer type towards the professional, while fewest occur in the opposing trend away from professionalism and in transitions from active part-timer to the detached farmer type (**Figure 3.9**). These transitions additionally demonstrate macro-drivers hold considerable influence over sectorial professionalism, as demonstrated by the high number of active part-timers switching to the professional type or away from detachment in a "Bright - ILIs" scenario.

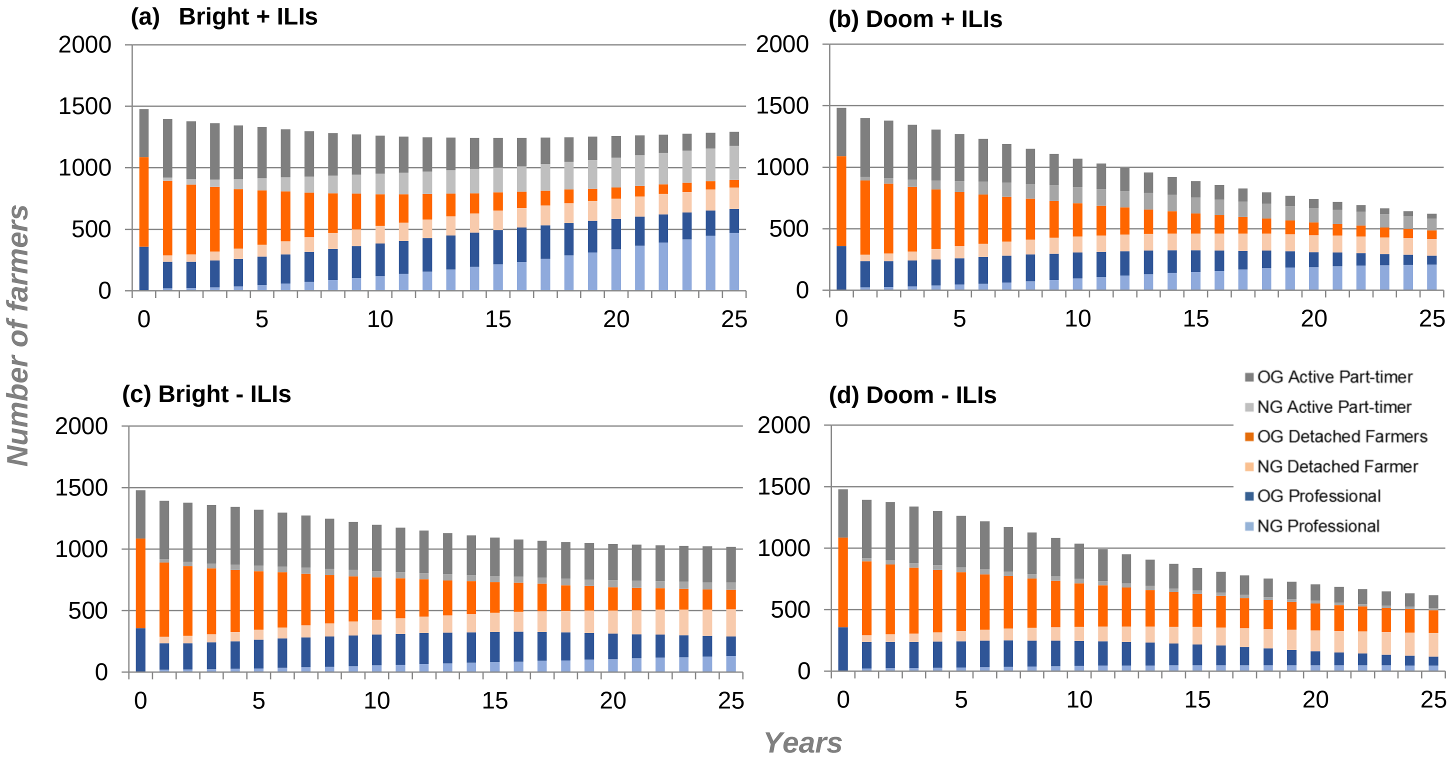

Figure 3.8 – Changing farmer typology composition amongst old and new generation farmers throughout a 25 year simulation under two contrasting Doom and Bright scenarios, with and without the implementation of ILIs ; NG = new generation farmer, OG = old generation farmer. Values are averages from 20 complete model runs.

Figure 3.9 – % Farmer typology composition following a 25 year simulation under two contrasting Doom and Bright scenarios, with and without the implementation of ILIs. The size of the arrows represents the ordinal importance of farmer type-switches based on the number of transitions throughout the simulation period. Values are averages of the final yearly time-steps from 20 complete model runs. The starting distribution is based on the result of the cluster analysis undertaken with the interview sample.

The extent of changes to plot ownership by farmer type class under each scenario with and without implementation of ILIs are illustrated in **Figure 3.10**. These maps represent the pixels with the highest frequency areas for each relevant farmer type class in turn corresponding to pixels with lowest standard deviations (< 0.35 / 1.0) among 20 simulations for each of the modelled scenarios. These "hotspot" areas were analyzed for correlations with the land suitability map, while additionally providing qualitative information on the extent of uncertainty and stochasticity of the spatial model outputs.

Between 20 and 22% of cultivated land in the region of Gera at the end of each simulation was identified as a hotspot area for one of the three farmer type classes. Active part-timers had the highest percentage of hotspot areas in all scenarios except "Doom – ILIs". Hotspot areas for the professional farmer type make up < 20% of majority areas for their type class in all simulations and were not at all identified in simulations that did not include ILIs. Comparison with the land suitability layer reveals all farmer types see a higher average land value of plots in Doom scenarios when compared to Bright, as farmers are more inclined to shrink their farming systems in Doom conditions and keep their most valuable plots. Highest average land suitability remains with professional farmers under each of the scenario simulations.

Land cover classes found greatest locational stability amongst the iterations within the "Bright – ILIs" scenario storyline, whereby 34% of total area was identified as a hotspot location, primarily a result of the location of intensified plots (57% hotspot area). De-intensified plots conversely found greatest variability in location amongst the iterations, as no hotspot areas were identified in three of the four scenario simulations. On average, plots that underwent long-term abandonment witnessed the highest average amount of hotspot area across the four scenario simulations (26%) (see SI for comprehensive results).

Figure 3.10 – Farmer typology ownership of olive plantations of Gera under constructed cadastral map, following a 25 year simulation under two contrasting Doom and Bright scenarios, with and without the implementation of ILIs.

3.3.3. Sensitivity analysis

Results of the sensitivity analysis are based on 20 iterations for every changing parameter under each of the four scenario storylines. This value was established after the coefficients of variation for the model outputs were calculated from an increasing number of runs. Coefficients of variation for total decline in farming population and increased abandonment extent were lowest in Doom scenarios (approximately 0.03 and 0.01 respectively) and highest for the "Bright + ILIs" scenario (0.16 and 0.17 respectively). While the majority of model outputs showed a stabilization of coefficient of variation values from 20 iterations, outputs related to changing average farm size and number of transitions between farmer types showed higher variation, with coefficient of variation values > 0.5.

The sensitivity analysis revealed that the model is particularly sensitive to the annual percentage of newcomers. Running the model with the maximum value of annual newcomers tested in the sensitivity analysis (5% of total population) resulted in more pronounced changes in Bright than in Doom scenarios, showing an average decline in abandoned plots (from baseline value outcomes) of 39% and 18% respectively. In a "Bright + ILIs" scenario, this limits the abandonment extent on average to 5% by the end of a 25 year simulation. In all scenarios, increasing the amount of annual newcomers to this maximum value leads to an increase in detached farmers at the expense of the remainder two farmer types.

Of the variables influenced by ILI implementation, their ability to increase probability of having willing successors appeared as the most influential under Bright conditions. Running the model without changes to this parameter resulted in a further 20% decline in the number of farmers and an 18% increase in the extent of abandonment. Under Doom conditions, model sensitivity was dependent on more parameters. Results in this scenario show a further decline in 9% of the farming population when excluding ILI influence on probability of successors, and an increase in 11% when excluding ILI influence on cultural drive or when excluding gradual declines to subsidies, compared to baseline conditions. Of the macro drivers, changes to olive oil prices most greatly affected extent of abandonment, plot intensification and amount of new generation farmers. Subsidies were on the other hand more influential to changes in farming typology composition, which generally proved considerably sensitive to changes in underlying drivers (see **Figure 3.11** and SI for comprehensive results).

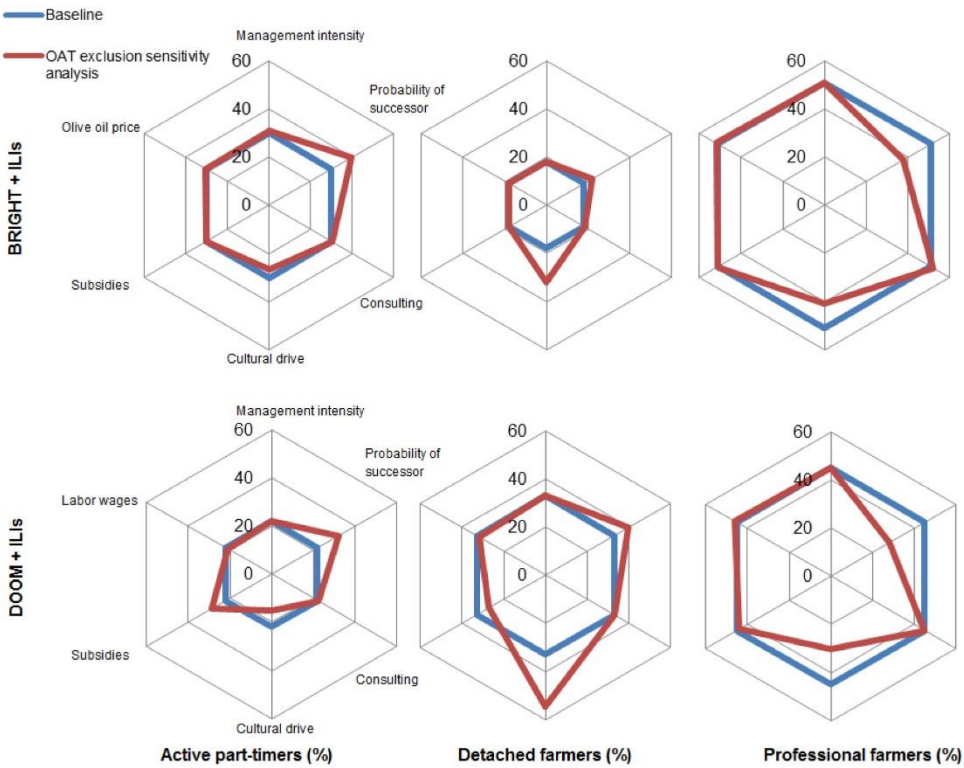

Figure 3.11 – Model sensitivity to parameters changed by multi-level drivers illustrated by a comparison between % farmer typology composition under baseline conditions and model runs excluding each of the affected parameters individually. Values are averages of the final yearly time-steps from 20 complete model runs.

3.4. Discussion

3.4.1. Model outputs: implications of the interplay between multi-level drivers, behavioral transformations and landscape change in Gera

This study sought to capture the divergent, alternative futures emerging from presently occurring discourses in the region of Gera. The principal findings derived from the model simulations are:

1. Only a combination of macro-drivers supporting sectoral profitability and implementation of ILIs reverses abandonment trends in the simulated period of 25 years and sustains the local farming population. The implementation of ILIs alone does not prevent abandonment and collapse of farming population.
2. The hypothesized ability of ILIs to maintain and promote a cultural drive amongst adhering farmers and to increase a farmer's probability of having willing successors is crucial for securing a future farming population and behavioral transformations towards professionalism. Subsidies play a role in the promotion of pluri-active (active part-timers) over detached farming.
3. Behavioral transformations, enhanced by ILIs, more frequently occur towards professionalism than detachment. This transition implies increased management intensity in the cultivated olive landscape.
4. Scenario results show a polarization of the farmer typology between professionals and detached farmers, with the active-part timer type not representing the prevalent type under any simulations.

The validity of model outputs lies primarily within their empirical derivation in an iterative approach. Comparison with similar modeling studies and past trends in local landscape and population change additionally demonstrate model outputs to be within reasonable magnitude and direction. Kaufmann et al. (2009) found economic factors to be more important than social influence in the adoption of organic farming in Latvia and revealed that the combination of the two factors allows for the greatest proportion of adopters. This is comparable to our findings demanding a combination of both sectoral profitability and behavioral transformations under ILIs to reverse abandonment trends within the simulated time-frame. In modeling agricultural landscape change in Lesvos for the late 90s and early 2000s, Kizos

& Spilanis (2008) found abandonment more closely related to professional farmers while hobby farmers, retired farmers and semi-professionals are forecast to maintain land in the future, similar to conditions portrayed in this study's "Doom – ILIs" simulation. While their model similarly foresees ongoing abandonment, differences arise in the characterization of the farmer typology, as professional farmers were hereby characterized as largely culturally driven and equally reluctant to give up the profession, and semi-professionals found to foresee disinvestments regardless of additional sources of income. Models converge in their sensitivity to the number of newcomer farmers and succession rates. Results by de Graaff et al. (2008) similarly show extreme extent of abandonment under Doom conditions, reaching total abandonment of olive plantations for one of the target areas within their simulated period (2005-2030).

Past changes illustrate an average decline in farmer population between 1961 and 2010 of 0.89% annually (ELSTAT, 2011); suggesting a population of approximately 1166 farmers if projected to the forecast year of this study. Abandonment throughout the period of 1960 – 2012 reached a rate of 34.17 ha per year (Bürgi et al., 2015), thus resulting in an increase from the present estimated 32% abandonment extent to 51% if extrapolated to the 25th year of simulation. Both historical trends are closest to outputs forecast under "Bright – ILIs" conditions requiring gradual increases in subsidies and olive oil prices; a worsening of past trends would thus be forecast by the model under continuation of the status quo.

These findings bring forward propositions whose implications should be explored in more detail. A primary consideration is the perceived vulnerability of a farming community that cannot sustain itself despite widespread mobilization due to the influence of external macro-level forces, placing emphasis and responsibility for supporting the sector on governance and policy instruments. While this study did not investigate feedbacks between ILIs and macro-drivers, the financial support and policy involvement hereby conceptualized as "external" can become endogenous if structurally inherent to the organizational properties of ILIs. In a study reviewing examples of ILIs across Europe, García-Martín et al. (2016) found a lack of funding, social capital, community cohesion and institutional support to be key barriers to the success of ILIs, identifying significantly fewer exogenous ILIs (established through external forces including law, regulation or subsidy) reporting challenges than endogenous ILIs (stemming from local community initiative alone). They additionally found hybrid organizations to frequently represent initiatives, made of partnerships between local authorities and civic organizations as well as public and private actors. Opportunity for successfully preserving the local olive farming sector and associated heritage thus partially depends on the very structure and emergence of ILIs, their exogenous nature and the involvement, both financial and participatory, of multiple and diverse stakeholders. Such findings are relevant to rural development across Europe, where novel community-based governance mechanisms are "urgently" needed (Pedroli et al., 2016).

The farmer typology and behavioral transitions identified shed additional implications for the policy domain. Subsidies retain considerable influence on the farmer typology composition, similarly to dynamics identified in the Mediterranean landscape simulated in the ABM of Acosta et al. (2014). Professionalism, hereby illustrated as inextricably linked with cultural motives, is crucial to the preservation of the agricultural landscape, yet macro-drivers are unable to substantially drive transitions towards this type without operating ILIs.

3.4.2.Methodological limitations

Workshop contributions from both cultural landscape experts and the local farming community, alongside results from the sensitivity and locational variability analyses, identify model limitations that in part reflect a wider, on-going discussion of complicatedness and implementation in (empirically based) ABMs (Brown et al., 2017; Sun et al., 2016). The model refinement process following the stakeholder workshop led to increased process abstraction (**Table 3.5**) in an attempt to avoid over-complication, yet risking oversimplification (Polhill et al., 2010). We identify key instances whereby the (deliberately) more abstract processes depicted in the ABM and its outputs may not sufficiently or adequately account for existing complexities, and discuss the implications of model uncertainty:

- Probabilistic processes are present in all three major, path-dependent, decision-making functions of farmers, resulting in the high coefficients of variations for type-switch occurrences and average plot size in particular. Probability values were set and adjusted following model calibration to provide sufficiently credible diversity in scenario outcomes while remaining within order of magnitude of historical trends. Nevertheless, these values remain difficult to validate. The sensitivity analysis (see SI) informs the effect altering the "calibration-factor" probability value holds on both landscape changes and behavioral transformations, acknowledging the resulting uncertainty in model outputs.
- Of significance are the model outcomes' sensitivity to the number of annual newcomer farmers arriving to Gera, as well as the number of willing successors. As the number of new arrivals to the regional sector is unknown, this finding provides scope for further investigation of labor migration in relation to the local olive farming sector, an exploration reinforced by the concerns expressed by the local farmer community throughout the workshop.
- Not all model variables were possible to assess via sensitivity analysis. Some variables were thus modelled based on a single parameterization. This includes the rates of change of the three macro variables altered in the scenarios, using values directly extrapolated from the study of de Graaff et al. (2008), and whose weights in the decision-making functions are based on rough, averaged estimations from the local workshop participants. Model sensitivity to the effect of inclusion/exclusion of subsidies in their potential to incentivize type-switches is an example whereby an effort towards higher abstraction clashes with local realities, as present active part-timers are less likely to meet necessary subsidy requirements due to their low share of agricultural vs. household income and potentially older age.

- Workshop discussions centered upon existing links between agricultural dynamics and those of other spheres (whether political, market-based or biophysical), for the large part absent in the ABM shown. Main reasons for not including these in the refined model relate to a desire to increase the presentation of the ABM as an exploration of socio-cultural determinants shaping local landscape change processes. We however recognize the omitted processes are fundamental to an accurate assessment of sectorial trade-offs (in the labor and land markets, for example), equally significant in driving land-based decision-making and largely unexplored within most ABMs of human-environment interactions (Brown et al., 2017).
- The model only partially incorporates system ruptures and "secondary feedback loops" as advocated by Le et al. (2012). Agents have internal memory and behave according to annual, in relation to past, events. Progressive increase or decrease in scale of their farming systems in turn may breach an area threshold and result in a type-switch. Such instances of *cumulative* change are however limited to scale-based decision-making behavior of individual farmers, and are absent in the consideration of, for example, cumulative responses by individual or collective agents to increasing ILI membership, advancing abandonment, oil price decline, etc. which may not progress linearly through time or may trigger (or be triggered by) novel responses.

These sources of model uncertainty would limit the predictive value of an ABM that is intended to be explorative in scope. The ABM explicitly sought to capture and illustrate landscape changes emerging from presently occurring farming discourses, rather than parameterizing variables from historical census or remote-sensing datasets. The model outputs are thus implicitly biased by the farmer's perspectives. Such an approach placed as much emphasis on the model-building process as on its outputs, and on structural as well as outcome validity, based on an understanding that increasing an ABM's credibility, legitimacy and salience demands these elements to be perceived by the ABM's users and audience, an effort more effectively achieved through their inclusion throughout the model-building process. The move from a more complicated to a simpler model structure following the stakeholder workshop strove for a more transparent and consistent presentation of the ABM as abstract and explorative, matching "extreme" scenario names to the artificial cadastral dataset simulated.

3.4.3. Reflections on ABM and stakeholder engagement in land use change research

Particular emphasis was placed on constructing the model in collaboration with the local community in an incremental/iterative process. The stakeholder workshop proved crucial as it allowed for a closer discussion of model processes and resulted in the derivation of many novel representations, while witnessing enthusiastic participation by the local stakeholder community and confirming the case for utilizing ABMs as explorative discussion tools in a set-up that favors their opening to critique (Johnson, 2015). The intuitive nature of the ABM is likely to at least partly result from the simplicity maintained in the set-up of the decision rules (largely composed of "if-then" queries rather than mathematical expressions) (Sun et al., 2016). Successful ABMs are widely perceived as able to achieve a sufficient yet minimal level of complexity in a bid to reduce uncertainty and error (Sun et al., 2016). The increased implementation of explorative, empirical ABMs of land use change, however, demands more complicated structures. Decreasing model complexity following iterative stakeholder consultation enabled joint discussion, identification and prioritization of all system components, facilitating a transition towards clarity, communication and "appropriate" complexity.

Empirical ABMs are increasingly integrated within qualitative and participatory approaches undergoing efforts to improve their exploratory role and communication potential to both the public and practitioners (demonstrated in the increasing number of "best-practice" publications, e.g. NetLogo visualization guidelines outlined in Kornhauser et al. (2009)). The workshop undertaken in this study aimed at discussing the multi-faceted aspects of the ABM in an afternoon session. Studies have shown value in focusing upon fewer elements of ABM structure and implementation over extended workshop sessions (see, for example, the backcasting scenario approach implemented by van Berkel and Verburg (2012)). Alternatively, Polhill et al. (2010) adopted constant and gradual model refinement at the interview stage itself. Companion modelling approaches have additionally shown rapid advancement and potential in addressing issues of calibration and validation in empirical ABMs (Brown et al., 2017), while adopting a more experimental approach suited to the exploration of socio-psychological determinants of decision-making.

Questions and actions remain in fulfilling this study's aims of "investigating the role of ABMs in stimulating societal discussions about management options". Model presentation and discussion has thus far included a relatively homogeneous audience; particularly within the local community, largely limited to farmers. In light of results demonstrating the necessity of "exogenous" involvement, discussion of the implications of the envisaged alternative landscape futures explored through the ABM should aim to incorporate a more diverse range of decision-makers and landscape users. While the ABM did succeed in stimulating relevant discussion amongst all the present participants, the workshop turnout remained low and discussion centered upon validating model outputs and processes and less on a discussion of alternative futures and interventions. While significant dynamics omitted in the ABM were identified by participants, discussion could have been enhanced by an assessment of model utility and reliability in light of these observations (Millington & Wainwright, 2016). Questions posed throughout the workshop to the local community investigating the expected number of ILI-adherent farmers in a "best-case" scenario revealed participants were largely divided in their predictions, mirroring findings of the primary interviews portraying a society split in pessimistic vs. optimistic forecasts on the future of the sector (see Zagaria et al. (2018)). Despite the questionable validity of such statements due to the low representativeness of the sample, these findings all cast extensive emphasis on the seemingly pivotal role of community engagement.

3.5. Conclusions

This study provides a mixed-method exploration of alternative futures of a Mediterranean cultural landscape prone to abandonment. We applied a novel conceptualization of behavioral transformations while placing emphasis on generational succession, an outlook often dismissed within ABM literature because of the relatively short time-scales addressed. It exemplifies an approach to study complex human-environment system interactions by means of combining an agent-based model in a stakeholder interaction context for consideration to the future management of cultural landscapes. The constructed model captures and illustrates the cumulative effect of demographic and landscape transitions, and, in doing so, draws attention to the critical hindrance structurally deficient policies and initiatives can inflict on the resilience of rural communities and agricultural heritage. While the model deliberately presents scenarios whose names are connotative of extreme or even unrealistic conditions, these scenarios emerged from the voices of a farming community that rejects a continuation of the status quo. The findings pave the way for improving rural development in the region and additional research across the valued cultural landscapes of the world to further address future management of cultural landscapes; further insight is needed in narrowing focus on new generation farmers and labor migration.

Acknowledgements

This work was supported by the European Commission FP7 HERCULES project (grant number 603447). We thank S. Heckbert and T. Haer for the technical support provided in coding the agent-based model. We would like to acknowledge the assistance of E. Pavlou, E. Bourgia, T. Tzimos, I. Christia and E. Kappa in undertaking interviews with land managers. We additionally thank all participants and facilitators present at the HERCULES workshop in Pappados on April 21, 2016. We would furthermore like to thank the anonymous reviewers who provided valuable feedback on earlier versions of this work.

Chapter 4

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

This chapter is published as: Zagaria, C., Schulp, C. J. E., Zavalloni, M., Viaggi, D., & Verburg, P. H. (2021). Modelling transformational adaptation to climate change among crop farming systems in Romagna, Italy. *Agricultural Systems*, 188, 103024. https://doi.org/10.1016/j.agsy.2020.103024

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.

4.1. 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 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 & 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 & 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 & 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 & Howden, 2012). Identifying cases where transformational adaptations may be necessary or desirable is therefore important, yet features of non-linearity, 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 & 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 4.2**, we outline the processes of model characterization (**section 4.3.2**) and parameterization (**section 4.3.3**). **Section 4.3.4** presents an overview of the climate, behavior and water policy scenarios explored, and is followed by a presentation and discussion of the modelling results.

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

Romagna (6’380 km^2), a historical region, administratively within the region of Emilia-Romagna (**Figure 4.1**), 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 & Povellato, 2012). Romagna is drought prone due to low precipitation rates and streamflow from the Apennines (Munaretto & 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 4.1, Figure 4.1**). 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 & 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 4.1**) (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 & Battilani, 2014), mirroring drought policy discussions taking place at the supra-national level (Stein et al., 2016).

Table 4.1 – 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 100m elevation) (Istituto Nazionale di Statistica, 2010).

		LRIC-West Romagna		LRIC-Romagna	
Characteristic	**Year**	**Hills**	**Plains**	**Hills**	**Plains**
No. of farms	2010	1807	7320	5544	10731
	1982	2994	13719	10277	22200
Utilized Agricultural Area (ha)	2010	23519	107106	63792	96561
	1982	32497	112790	80979	104858
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

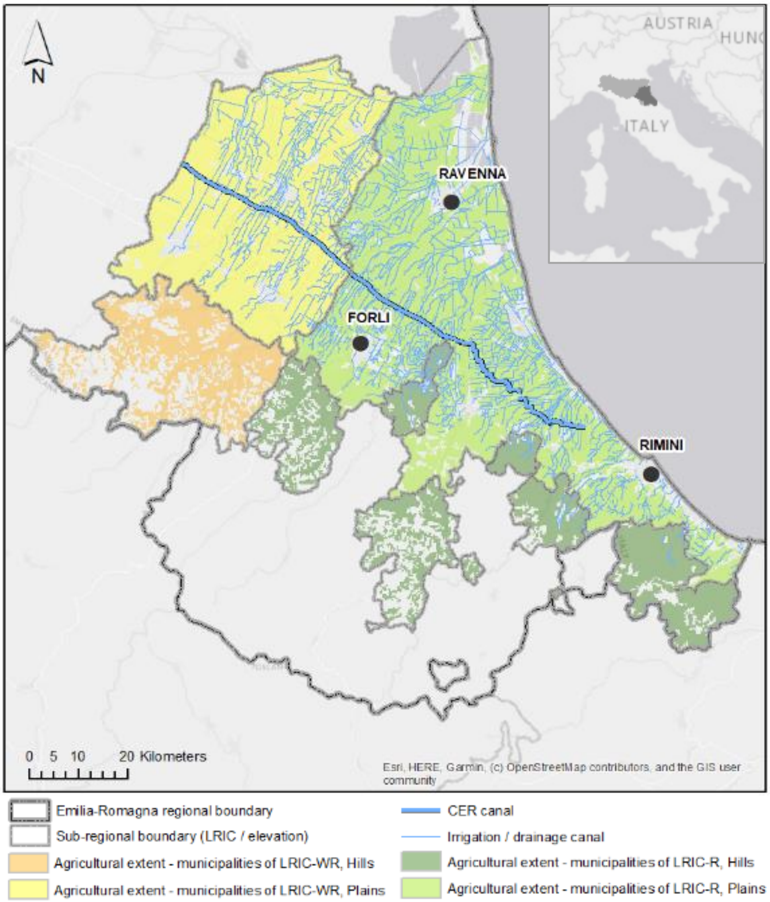

Figure 4.1 – Characteristics, location, and subdivision of our case study area within the Emilia-Romagna region (NE Italy). The case study extent is defined by the 58 municipalities in the Emilia-Romagna region under management of the LRIC of Romagna or Western Romagna with predominantly crop-based farming systems (SI) (ESRI et al., n.d.; European Environment Agency, 2016; Regione Emilia-Romagna, 2017a, 2017c, 2017b).

4.3. 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 4.3.1-4.3.2**, 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 4.3.3**, 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 4.3.4**).

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 SI).

4.3.2. Model overview and characterization

4.3.2.1. 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 & 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.

4.3.2.2. Entities

Details on the model entities characterizing the ABM are provided in **Table 4.2**. These were identified through the analysis of interviews and local literature, and structured as follows (the SI 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 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 4.2**). 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" (van der Ploeg & 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 4.3**). 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) (SI).

- *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 4.3**). 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.

Table 4.2 – Overview of core model entities and attributes (respective parameterization references are listed in the SI); policy attributes are largely absent as these principally operate by influencing other attributes (e.g. market prices) depending on the scenario explored (see **section 4.3.4**).

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

4.3.2.3. Processes and scheduling

The ABM is structured around three principal "sub-models" (**Figure 4.2**), 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 SI 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 4.3.4**), (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 0-1), 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 4.3**). 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 2.2km from the farm). If obstacles are present, the farmers do not implement the selected adaptations, nor do they 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 4.3.2.2**). Farmers only *pursue* one strategy at a time and will maintain any diversification activities when changing toward an expansive or contractive 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.

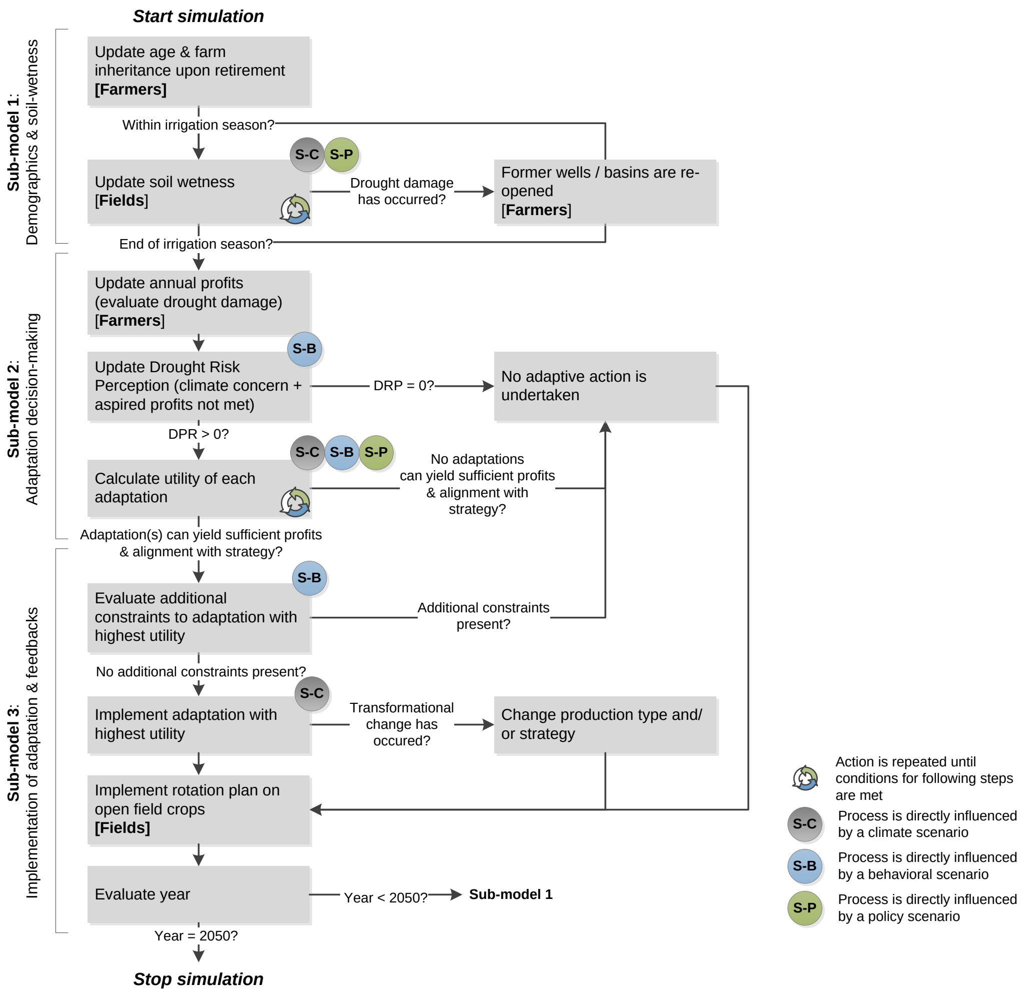

Figure 4.2 – Overview of primary processes undertaken by fields and farmers chronologically throughout a yearly model run. Points of influence are illustrated for each scenario group (climate, behavior, and policy).

Table 4.3 – 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.

		Moderating variables			
Adaptation	**Potential for transformation**	**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

4.3.3. 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 >100m elevation) to the more detailed, regional, iCOLT-2017 dataset (Arpae Emilia-Romagna, 2017) (available only in areas <100m 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 SI). A minimum of 5ha 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 sub-classes (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 (SI). 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 m^3/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 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 SI.

4.3.4.Scenarios and sensitivity analysis

Climate change scenarios provide baseline settings using the parameter values outlined in **section 4.3.3.** 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 4.4**):

- *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 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 4.3.2**). 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

[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)

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 4.4**). 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 SI). In this case, results are reported for simulations run under RCP 2.6 climate scenario conditions alone (Schouten et al., 2014; ten Broeke et al., 2016). All results are based on the averages of 5 repetitions.

Table 4.4 – 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.

	Behavior scenarios				Policy scenarios			
Model variable	**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%

4.4. Results

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

All scenarios reveal similar trends in terms of which adaptations are preferred and implemented by farmers (**Figure 4.3**). 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 (SI) 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.

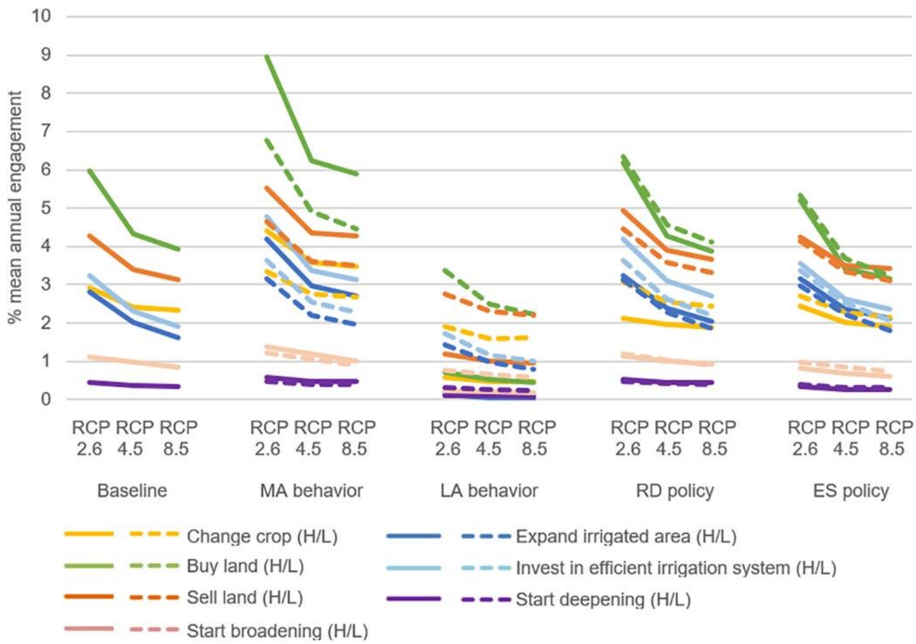

Figure 4.3 – Mean annual share (%) of farmers engaging in each type of adaptive action throughout a simulation (2017-2050) under scenarios exploring the influence of climate, farmer behavior, and water policy. Dashed lines illustrate results under low bound scenario conditions, while solid lines illustrate results under high bound scenario conditions (**Table 4.4**).

4.4.2.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%) (**Figure 4.4c**). Widespread irrigation expansion in MA scenarios (**Figure 4.5**) 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) (SI). 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 (SI). Despite larger increases to irrigated area than in ES policy and baseline scenarios, RD scenarios witness fewer irrigation withdrawals (SI) and therefore only hold a small potential to mitigate drought damages when compared to baseline scenarios (**Figure 4.5**). 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 (**Figure 4.4c**).

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%) (**Figure 4.4c**). 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 (SI). 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 (**Figure 4.5**). Compared with baseline conditions, however, ES policy scenarios see stronger declines to regional agricultural revenues despite a smaller share of cropland witnessing drought damage (SI).

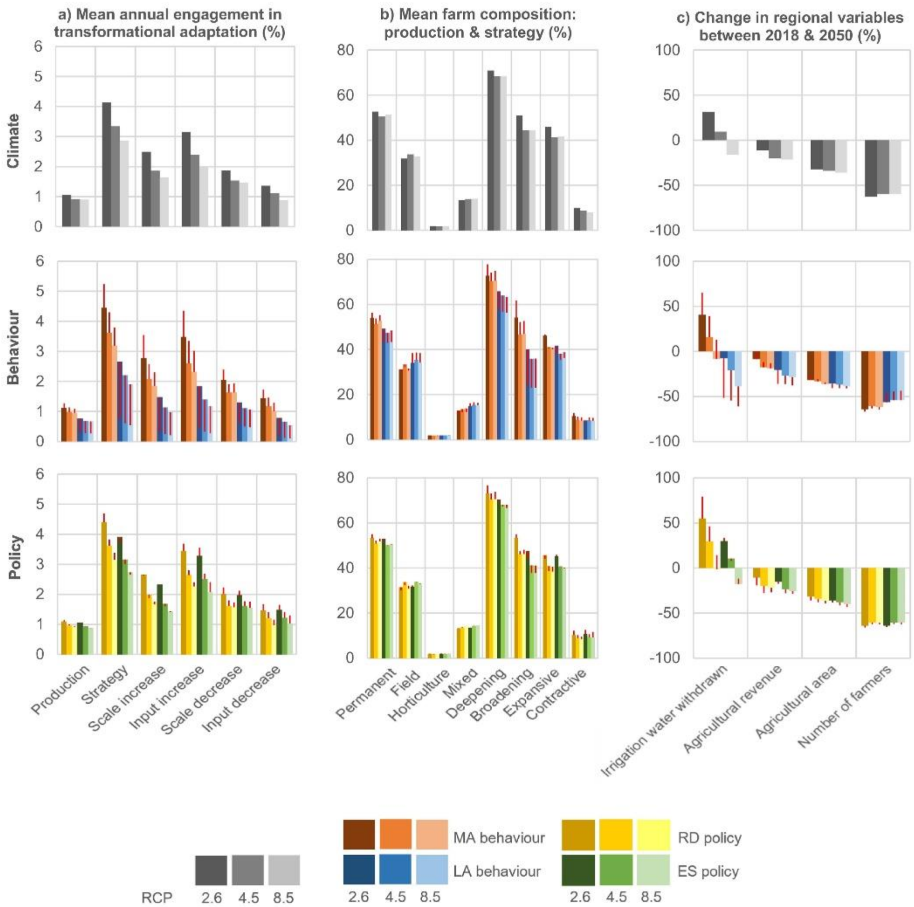

Figure 4.4 – Influence of changing climate, farmer behavior, and water policy on (A) the annual % mean share of farmers implementing transformational adaptations throughout a simulation (2017-2050), (B) the annual % mean share of farmers belonging to each production type and implemented* strategy throughout 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 4.4)**, with red bars illustrating results under the higher bound scenario values (Scenario H, **Table 4.4**). Tabulated results are illustrated in SI. *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.

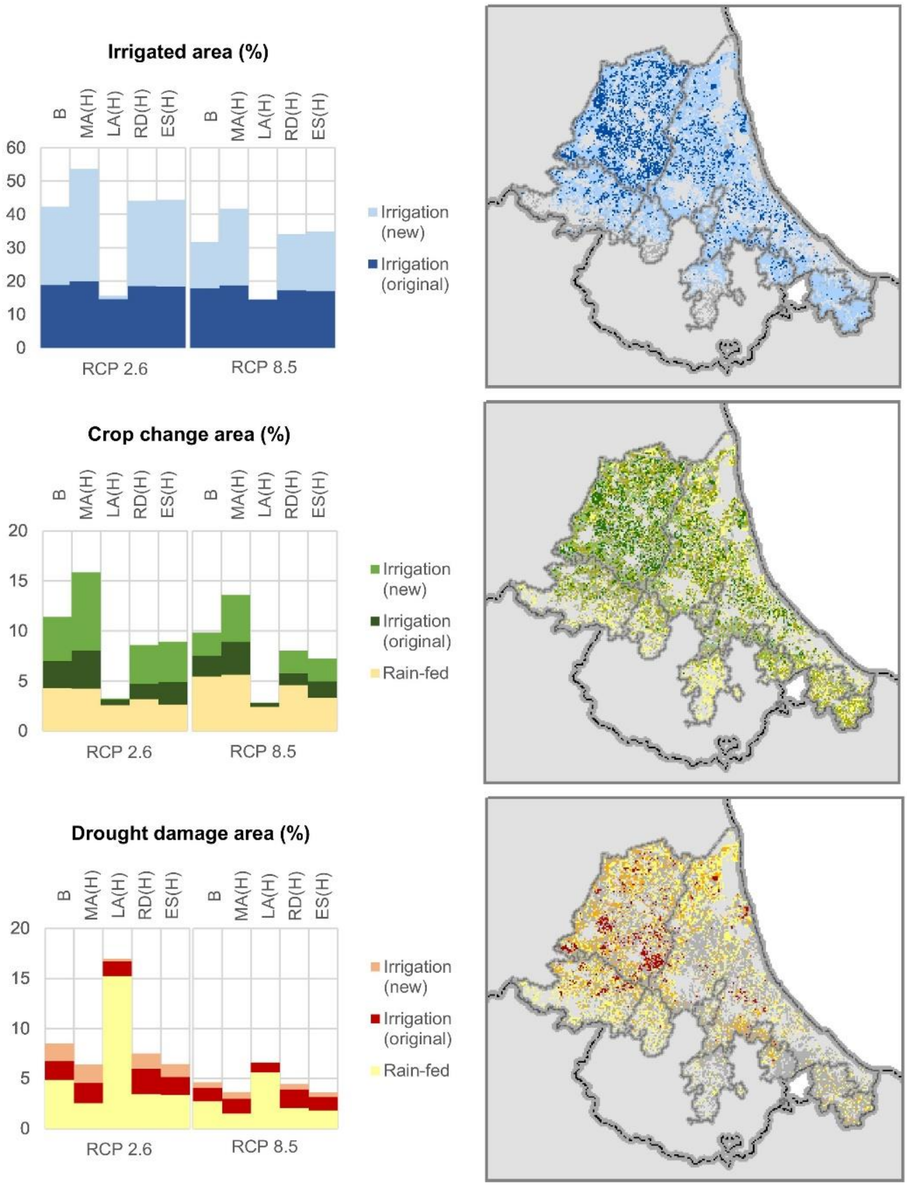

Figure 4.5 – Influence of climate (B), behavior and water policy scenarios (high bound conditions) on the share of agricultural area witnessing irrigation expansion, crop change and drought-induced damages to production in Romagna. The share of agricultural area is calculated based on the agricultural 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.

4.4.3. What role for transformational change?

Figure 4.4a 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 (SI), 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. 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% (**Figures 4.3, 4.4**).

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% (SI). Transformations relating to crop changes (although less frequent than those relating to scale) further contribute to scale enlargement trends as these involve transitions toward 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 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 (**Figure 4.4a**), therefore partly compromising the policy goal to reduce irrigation (SI). 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 (SI).

4.5. Discussion

4.5.1. Implications of scenario findings

Our scenario results are largely in line with historical trends (SI). 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 amongst 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 & 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, Lemos, and Nelson 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.

4.5.2.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, Travis, and Wilbanks (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 (SI).

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, Brown, and Rounsevell (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).

4.6. 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.

Acknowledgements

This research was supported by the European Research Council (ERC) through the European Union's Seventh Framework Program's LUC4C (Grant No. 603542) and GLOLAND (Grant No. 311819) projects, as well as the Horizon 2020 Research and Innovation Program's PROVIDE (Grant No. 633838) and CONSOLE (Grant No. 817949) projects. The authors would like to thank all interview participants, the Land Reclamation and Irrigation Consortium of Romagna and Western Romagna for facilitating the interviews, and M. Wens for helpful discussions on climate and agent-based modelling. They are additionally grateful to three anonymous reviewers for their insightful feedback on earlier versions of this manuscript.

Chapter 5

Potential for land and water management adaptations in Mediterranean croplands under climate change

This chapter is under review in *Agricultural Systems* as: Zagaria, C., Schulp, C. J. E., Malek, Ž., & Verburg, P. H. Potential for land and water management adaptations in Mediterranean croplands under climate change.

Abstract

The Mediterranean Basin has been identified as a climate change "hotspot", a region where increased warming and drying are expected to occur at rates faster than the global average. Increasing scientific attention has therefore been drawn to the repercussions of climate change for the Mediterranean's diverse and valued agricultural sector. The extent to which these repercussions vary throughout the region, owing both to a non-uniform distribution of climatic hazards and to uneven adaptive capacities of farmers, remains however unquantified. We hereby provide a comprehensive spatial assessment of the potential to implement different farm-based land and water management adaptations across the Mediterranean's croplands, and evaluate the extent to which different regions see a match or a mismatch between areas of adaptation need and areas of adaptation capacity. This approach made use of spatial multi-criteria analysis to evaluate the suitability of the adaptations, and relied on the Ecocrop climate suitability model and climate data on changing duration or frequency of extremes to identify areas of adaptation need under a high-end climate change scenario. The adaptations explored in this work span a range of sustainable approaches addressing different components of the farming system (soil-based, water-based, and crop-based adaptations). For each sub-system, we compared the potential to implement an adaptation representing an incremental change vs. one involving greater transformation. Results indicate a worsening of climatic conditions for all croplands in the region, and particularly within the Mediterranean extents of Egypt, Turkey, Greece, Spain, Morocco, Bosnia and Herzegovina, and Israel. In more than half of these countries, more than 60% of highly affected Mediterranean areas, on average, see no tangible potential to implement adaptations. Importantly, potentials for adaptation, and particularly of transformational adaptations having the greatest hypothesized capacity to buffer against the effects of climate change, are found to be lower within areas where the most adverse climate hazards are forecast to occur. For regions found to be approaching so-called limits to adaptation, this research contributes to growing calls for consideration of more transformational options, alongside the opportunities and sacrifices these options entail. For regions where considerable (yet unrealized) adaptation capacity is found to match areas of adaptation need, this paper instead presents a basis for further investigation on how to bridge adaptation capacity and preparedness.

5.1. Introduction

Increased warming and drying throughout the Mediterranean Basin is expected to occur at a faster rate than the global average (Cos et al., 2021; Cramer et al., 2018; Lionello & Scarascia, 2020), owing to the region's unique morphology and positioning along a transition zone separating an arid southern climate from a more temperate north (Giorgi & Lionello, 2008; Skuras & Psaltopoulos, 2012). Exposure to these trends is forecast to differ throughout the Mediterranean itself, with areas lying below the 38th parallel north displaying a higher likelihood of intense precipitation and hydrological extremes (Lionello & Scarascia, 2020). Uneven regional impacts to agricultural production are consequently expected to take place (Grasso & Feola, 2012). Yield instability in response to increasingly frequent and severe drought and heatwave events has already partly impacted local crop production in recent decades, with greatest damages manifested in cereal crops (Brás et al., 2021). In the future, significant yield declines have been predicted for many regionally important productions, including cereals, legumes, tuber crops, tomatoes, and sunflower, while characteristic olive groves and grapevines are expected to face more moderate but still locally important impacts, affecting fruit quality alongside production (Cramer et al., 2018).

Adaptation is therefore a key concern for Mediterranean farming communities wishing to maintain their current systems and productivity levels under increasingly adverse climatic conditions. To some extent, the region can rely on the traditional know-how of its rural population, which has long implemented land and water management practices to secure crop production by controlling less favourable environmental conditions (Ruiz et al., 2020). These more traditional practices have over time also been complemented by further technological innovations and large-scale infrastructural projects. Irrigation expansion across the Mediterranean has doubled in the past forty years to cover a fifth of total cropland (Daccache et al., 2014), while drip irrigation ranges from <5% of the irrigation system share in Albania, Algeria, Croatia, France, Portugal, and Turkey, to >80% in Cyprus and Jordan (Jägermeyr et al., 2015). These values exemplify that while adaptation is common, the uptake of specific practices is not uniform throughout the territory. The extent to which a lack of uptake in some regions is due to hard limits or soft constraints, or even the undesirability of certain practices deemed maladaptive under specific circumstances, remains however unclear.

Recent research aiming to quantify the adaptive capacity of different actors, i.e., "the ability to design and implement effective adaptation strategies" or to "reduce the likelihood of the occurrence and/or magnitude of harmful outcomes" of climate-related hazards (Brooks & Adger, 2005), has attempted to explain why the extent of different adaptation implementations varies across a territory (e.g., Grasso & Feola (2012)). Adaptive capacity is adaptation specific and has previously been captured, among others, by addressing both socio-economic and biophysical factors determining enablers, hard constraints and limits to its adoption (Iglesias, Mougou, et al., 2011). More specific examples of such regional determinants have on the one hand addressed factors associated with agricultural innovation, financial assets, and human resources, and on the other placed emphasis on biophysical constraints tied to a particularly dry and water-scarce territory (Iglesias, Mougou, et al., 2011). In order to ensure the "effectiveness" of the adaptation practice, the adaptation research community is increasingly stressing the importance of differentiating between adaptations which aim to merely substitute or improve the efficiency of current practices, and adaptations which involve a more fundamental transformation of the farming system, a component that may be required when the impacts from climate change are foreseen to be particularly severe (Rippke et al., 2016; Wezel et al., 2014).

Despite the urgent adaptation challenge faced by the Mediterranean, the extent to which adversely affected farming communities have or lack the potential to implement different farm-based adaptations is unknown, limiting targeted action and reflection on the need for more transformational change. Our work aims to bridge this knowledge gap by means of spatial analysis, exploring the potential of different sustainable land and water management strategies which include transformational adaptations hypothesized to hold greater resilience against climate change. Our first research objective aims to spatially assess the suitability of sustainable land and water management practices within croplands across the Mediterranean Basin. Secondly, we aim to evaluate the extent to which the potential of such practices overlaps with areas forecast to witness the most adverse changes to climatic conditions, quantifying matches or mismatches between adaptation potential and needs. Finally, we aim to present a synthesis on which cropland areas are more, or less, likely to remain viable under climate change, and under which conditions.

5.2. Methods

We evaluated potential spatial (mis)matches between cropland areas projected to witness the most adverse changes to climatic conditions (hereafter referred to as "climate impacts") and areas deemed suitable for the implementation of sustainable farm-based adaptations across the Mediterranean Basin. The climate impact analysis is based on a "high-end" climate change scenario (>2^{o}C warming by the end of the century) to identify the maximum extent of adaptation that may be required. **Section 5.2.1** outlines the steps involved in the climate impact analysis. In **section 5.2.2**, we outline the process of determining suitability for different adaptation strategies, based on the present-day occurrence of their socio-economic and biophysical determinants. In **section 5.2.3**, we briefly outline how the derived maps outlining climate impacts and adaptation suitability were combined to evaluate potential matches and mismatches (**Figure 5.1**).

We focused on areas producing regionally representative crops, and, following Daccache et al. (2014), selected olive, grape, citrus, and wheat as the most "strategic, traditional and representative crops for the Mediterranean region", tomato as the most representative vegetable crop, and sunflower and cotton as representative energy and industrial crops. Henceforth, references to "cropland" areas therefore refer solely to areas under the production of these crops which represent the vast majority of Mediterranean cultivated areas (Daccache et al., 2014). We additionally narrowed our selection of farm-based adaptations to six strategies targeting a farm's soil, water, or crop component, all aiming to address the concurrent climate risks identified in **Section 5.2.1**. These adaptations were identified within recently published reviews synthesizing options for the Mediterranean region, prioritizing adaptations with widespread applicability across places and farm types (see details in SI).

We additionally distinguished whether the adaptations represented examples of incremental vs. transformational change (**Table 5.1**). Following the approach set out by Rippke et al. (2016), incremental adaptations were defined as adaptations which require less time and effort to implement, and therefore typically involve a lower degree of system change and refer primarily to crop management alterations. In this research, incremental adaptations were represented by the implementation of drip irrigation, crop variety change, and reduced tillage. In contrast, transformational adaptations are defined as those involving change across the crop or farming system and beyond the introduction of a single practice, thereby requiring greater time and effort to implement than incremental adaptations. We explored irrigation expansion, crop change, and the implementation of conservation agriculture as examples of transformational adaptations. The categorization of practices as either incremental or transformational was deemed important as transformational adaptations are further defined as actions that are more likely to be effective, and thus required, in significantly affected areas and where incremental approaches are likely insufficient (Rippke et al., 2016; Wezel et al., 2014). We acknowledge that multiple other definitions of transformational adaptation in agriculture have been put forward by the scientific community, with some definitions referring to adaptations addressing the root causes of vulnerability and thus including, for example, institutional changes taking place beyond the farm (Fedele et al., 2019), as well as adaptations involving a change in structure and organization which may include farm relocation or exit (Panda, 2018). These examples thus refer to both a broader and deeper view of change than that explored in our work.

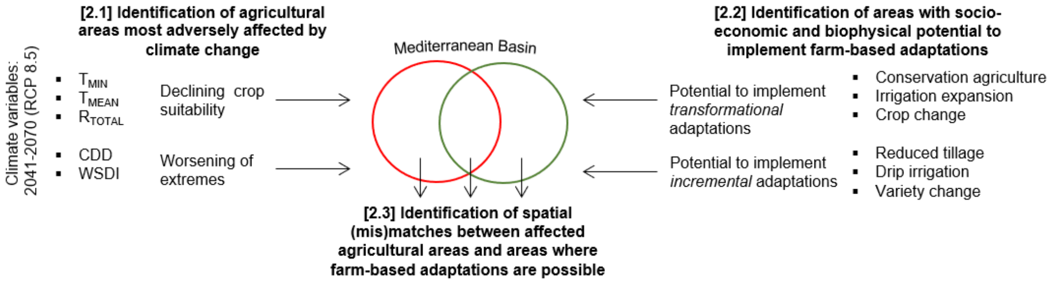

Figure 5.1 – Illustration of methodological workflow. We first identified Mediterranean regions forecast to be most adversely affected by climate change through declining crop suitability (determined by monthly minimum and average temperature (T_{MIN}, T_{MEAN}) and total monthly precipitation changes (R_{TOTAL})) and worsening of climatic extremes (maximum Consecutive Dry Days (CDD) and Warm Spell Duration Index (WSDI)). We then mapped areas with varying potential to implement incremental or transformational adaptations, evaluating whether these matched areas of climatic impact.

Table 5.1 – Matrix of selected farm-based adaptations and categorization according to the farm's water, soil, or crop component and type of adaptation.

	Water-based	Soil-based	Crop-based
Incremental adaptation (lower degree of time, effort, and system change)	Drip irrigation	Reduce tillage (to increase soil water retention)	Variety change (toward more climate resilient varieties)
Transformational adaptation (higher degree of time, effort, and system change)	Irrigation expansion (within rainfed areas)	Conservation agriculture (to increase soil water retention)	Crop change (toward more climate resilient crops)

5.2.1. Climate change impact analysis

Climate change impacts were assessed through the analysis of declining crop suitability for our selected crops (**section 5.2.1.1**), and through increases in the occurrence or duration of agro-climatic extreme events (**section 5.2.1.2**). We conducted a literature review to identify which extreme events were of most relevance to the selected crops (SI). All climate analysis was based on bias-corrected CMIP5 data, at a spatial resolution of 0.5°x0.5° on a lat-lon grid, downloaded from the Copernicus Climate Change Service portal (ECMWF, 2021). The analysis was based on the means of 5 General Circulation Models, notably IPSL-CM5A-LR (IPSL, France), NorESM1-M (NCC, Norway), HadGEM2-ES (UK Met Office, UK), MIROC-ESM-CHEM (JAMSTEC, Japan) and GFDL-ESM2M (NOAA, USA) for the Representative Concentration Pathway (RCP) 8.5 representing an unconstrained, high greenhouse gas emissions scenario (Riahi et al., 2011). Model selection matched data availability for the bias-corrected pre-calculated agro-climatic extreme event indicators (**section 5.2.1.2**). Areas of climatic impact from both analyses were overlayed on current production areas to quantify affected hectares. Spatial data on harvested hectares for wheat, sunflower and cotton were sourced from the SPAM2010 dataset (You et al., 2014), while data for citrus (hereby represented by orange and mandarin, tangerine, and clementine), tomato, olive and grape were sourced from Monfreda et al. (2008).

5.2.1.1. Crop climate suitability mapping

To determine crop climatic suitability, we made use of the Ecocrop model and its respective database (Hijmans et al., 2001; Ramirez-Villegas et al., 2013). The Ecocrop model determines spatial, climatic suitability by evaluating the extent to which monthly average minimum and mean temperature values, as well as total precipitation, exceed crop-specific thresholds. It then utilizes information on a crop's average growing period length and independently calculates temperature and precipitation suitability across all possible growing periods within a year. From this, the joint suitability value corresponding to the most suitable growing period is selected and summarized into a suitability map outlining unsuitable (0) to suitable (1) growing regions (full details in SI). Ecocrop therefore assumes farmers adjust their sowing dates to match the most viable potential growing season. We used the model database's default values on growing period length and climatic thresholds (FAO, 1994). Despite the model's coarse temporal resolution and representation of crop-climate dynamics, it has been deemed suitable for deriving a general indication of climate change impacts on shifting crop climatic niches (Manners et al., 2021). We used projected (2041-2070) climatic data and compared the resulting suitability values to the results from our reference historical period (1981-2010).

5.2.1.2. Agro-climatic extremes mapping

The conducted literature review revealed drought, heat stress, frost, cold stress, and heavy or prolonged precipitation to be the direct, extreme climatic events with the greatest adverse influence on the selected crops (SI). Respective agro-climatic indices for these events were identified in the overview of climate extremes indices of the Expert Team on Climate Change Detection and Indices (Sillmann et al., 2013) and were sourced from the Copernicus Climate Change Service portal (ECMWF, 2021). For each indicator, differences were calculated between the future climate change period (2041-2070) and the historical reference period (1981-2010) (SI). Results revealed a geographically widespread worsening of conditions for heat stress (warm spell duration index (WSDI), i.e., count of days per season with at least 6 consecutive days when daily maximum temperature exceeds the historic 90th percentile) and drought (maximum number of consecutive dry days (CDD), i.e., longest consecutive number of days with daily precipitation <1mm). These two indices were therefore the only ones utilized in subsequent analysis for the evaluation of impacts from climatic extremes. For maximum CDD, we investigated the change in the average annual sum of seasonal maximum CDDs, while for WSDI, we investigated the change in the average annual sum of consecutive "heatwave" days. For both WSDI and maximum CDD, we divided the resulting increase in frequency or duration across the Mediterranean basin in 3-quantiles (tertiles), and ultimately identified the most adversely affected areas as those witnessing increases belonging to the second or third highest tertile in both indices (i.e., areas of high concurrent risk), alongside areas of declining crop suitability.

5.2.2. Adaptation suitability mapping

The adaptation suitability mapping was based on spatial multi-criteria analysis beginning with a literature search to identify, for each adaptation, the present-day local biophysical and socio-economic constraints and determinants of suitability, as well as the availability of spatial data for respective proxies (Oakleaf et al., 2019). The working resolution for the adaptation suitability mapping, and so for the final spatial (mis)match analysis, was approximately 10km by 10km, matching the resolution of the crop data. The determinants for each of the mapped adaptations are outlined in **Table 5.2**, while rationale for their inclusion, alongside further methodological details can be found in the SI.

5.2.2.1. Drip irrigation and irrigation expansion in rain-fed areas

The approach for mapping potential expansion of drip irrigation was borrowed from the methodology of Prestele et al. (2018) and adapted to an irrigation context. Datasets representing the identified determinants of suitability (hereafter termed "adoption factors", **Table 5.2**) were clipped to the national, agricultural extents of Mediterranean countries, masked to exclude areas where hard constraints were in place, normalized, and combined in a simple additive approach into a single (re-normalized, 0-1) "adoption index", with each factor arbitrarily holding equal weight. National reported estimates on the current implementation of drip irrigation (Jägermeyr et al., 2015) were then downscaled to the grid-cell level by progressively assigning hectares to pixels with the respective highest adoption index values, thus composing a present-day adoption map. A high-potential future adoption suitability map was subsequently generated by assuming all areas with adoption index values at or below the lowest value to which present-day drip irrigation had been assigned, to represent regions where adaptation is possible, but least likely. The downscaling procedure and final adoption potential map was limited to areas under production of crops suited to drip irrigation (based on Fischer et al. (2021); Jägermeyr et al. (2015); Sauer et al. (2010)), and only to their irrigated shares. Irrigated crop shares were sourced from the SPAM2010 dataset and MIRCA2000 dataset (Portmann et al., 2010) for cropland areas outlined by Monfreda et al. (2008) which extend beyond SPAM2010.

Spatially explicit data is currently available on areas equipped with irrigation infrastructure, and share of irrigated cropland (Siebert et al., 2013). The potential suitability for irrigation expansion was therefore mapped differently from the other adaptations. We followed the approach of Malek & Verburg (2017) and undertook a binomial logistic regression analysis to investigate the contribution of different socio-economic and biophysical factors to the presence of irrigated cropland (Siebert et al., 2013). We made use of the same 20 factors used in the Mediterranean analysis of Malek & Verburg (2017), and added information on poverty, land tenure, farm size, crop type, irrigation water availability and protected area networks as these were the additional factors we identified as relevant in our review of predictors and available spatial proxies (SI). The results of the regression (SI) were used to generate a potential adoption index (normalized, 0-1) for irrigation expansion, limited to currently predominantly rain-fed areas only (all areas with >10% of area equipped with irrigation were excluded). Here, again, we identified the lowest index value at which irrigation was already present and assumed pixels with values at or below this threshold to represent the lowest likelihood for potential expansion. In order to only illustrate the potential for *sustainable* expansion, we further excluded areas which will not be able to undergo irrigation expansion from groundwater or surface resources (under both "hard" or "soft" infrastructural approaches) while also maintaining ecological flow requirements in a 3^{o}C warming climate change scenario, based on the data of Rosa et al. (2020).

5.2.2.2. Reduced tillage and conservation agriculture

Mapping the suitability of reduced tillage and conservation agriculture followed the same approach as for drip irrigation, based on Prestele et al. (2018). National estimates on present-day adoption were sourced from EUROSTAT (2020), for reduced tillage, and Kassam et al. (2019) for conservation agriculture. For this latter practice, the downscaling procedure was limited to arable crops within medium and large-scale fields, as conservation agriculture is currently thought to be negligible within subsistence farming systems (Derpsch et al., 2010), yet under the future expansion scenario it could be implemented within permanent crops as well as on smaller fields (all equally weighted adoption factors are listed in **Table 5.2**). The adaptation potential maps therefore cover all cropland and do not comprise any exclusion areas for these two adaptations. While the adoption factors for both practices were found to be the same (SI), the current extent of implementation of conservation agriculture is lower than that of reduced tillage. Accordingly, the minimum adoption index values indicating the threshold at which conservation agriculture may be implemented are higher for this practice, suggesting stronger relative "costs" (e.g., requiring lower poverty levels, greater farm size) to its implementation.

5.2.2.3. Climate-resilient varieties and crops

Crop varieties can hold specific climate-resilient traits resulting in stress avoidance, stress escapism, and/or increased stress tolerance (Debaeke et al., 2017). We hereby focus specifically on the capacity of different varieties to increase tolerance to drought and heat stress. The Ecocrop database does not provide variety-specific climatic thresholds for our selected crops. To evaluate the extent to which an alternative or new variety can avoid future crop suitability decline, we re-mapped future crop suitability by increasing the Ecocrop model's threshold values for "Maximum optimal temperature" and "Maximum absolute temperature" values by 10% for each crop, and reducing "Minimum absolute precipitation", "Minimum optimal precipitation" and "Maximum optimal precipitation" values by 20%. These thresholds were implemented following Manners et al. (2021), and were found to be plausible for our selected crop productions for which variety-specific threshold values could be identified in the literature (notably grape, olive, wheat, and cotton) (Barranco et al., 2005; Hannah et al., 2013; Kakani et al., 2005; Porter & Gawith, 1999) (SI). We looked at the potential of variety change to improve climatic suitability within existing production areas only. The present-day suitability for each crop was subtracted from its respective future suitability under variety change to identify areas where suitability will increase by at least 0.1 on Ecocrop's 0-1 suitability scale. We then constructed an adoption index layer (normalized, 0-1) within these areas of increased suitability only (all other areas were excluded). We assumed different varieties to be suited to the same, non-climatic biophysical characteristics as their present-day species distributions (e.g., slope, soil types); the adoption index was therefore based solely on equally weighted socio-economic factors (**Table 5.2**).

With regards to crop changes, we searched peer-reviewed literature for proposed climate-resilient crops (Acevedo et al., 2020; Baltzoi et al., 2015; Gómez-López et al., 2019; Lavini et al., 2014; Rezaei et al., 2015; Thomas, 2008; Van Zonneveld et al., 2020), as well as news items from the region reporting evidence of production changes (Kuebler, 2020; Malsang, 2019). From this preliminary list of resilient crops, we narrowed our selection to those which held favorable climatic conditions (i.e., higher simultaneous heat and drought stress tolerance) then our originally selected productions according to their climatic thresholds in the Ecocrop database. We then narrowed our selection further by focusing on those crops which have been undergoing harvested area increases in the region in the 2000-2018 period, and are more profitable in comparison to current crops (i.e., have greater agricultural production values) (FAOSTAT, 2021). We ultimately investigated the scope of introducing millet (favorable potential replacement to wheat), pistachio (favorable potential replacement to tomato, wheat, grape, orange, and mandarin), and date (favorable potential replacements to sunflower, tomato, wheat, orange, and mandarin), as these crops allowed for the greatest number of possible transitions and represent both permanent and annual crops. Following the same criteria, we additionally scoped the replacement potential within the original crop productions (identifying olive as a potential replacement to tomato, grape, wheat, orange, and mandarin, and sunflower as a potential replacement to orange). No alternative or new crops were identified as suitable replacements for cotton or olive. We investigated the potential for crop changes only within areas where a crop change resulted in an increase in agricultural climatic suitability of at least 0.1 on Ecocrop's 0-1 suitability scale (all other areas were excluded). In contrast to variety change, the adaptation potential index (normalized, 0-1) accounted for equally weighted biophysical factors (slope and soil characteristics, **Table 5.2**) in addition to socio-economic factors. Slope and soil characteristics were additionally used to identify further exclusion areas where crops could not be implemented.

Table 5.2 – Identified biophysical and socio-economic determinants comprising the adoption indexes (i.e., not including exclusion factors) for the investigated adaptations and respective spatial proxies and datasets utilized in this study (rationale for inclusion is outlined in SI).

		Water		Soil		Crop	
Adoption factor (proxy)	**Proxy data source(s)**	**Drip irrigation**	**Irrigation expansion**	**Reduced tillage**	**Conservation agriculture**	**Variety change**	**Crop change**
Slope (%)	(Fischer et al., 2008)	✓	✓				✓
Median elevation (m)	(Fischer et al., 2008)		✓				
Soil properties (electric conductivity, exchangeable sodium percentage, calcium sulphate, calcium carbonate, soil texture, drainage, sand and clay content, cation exchange capacity (clay), soil pH, reference soil depth and/ or soil phase, coarse fragments, organic carbon content)	(Fischer et al., 2008)	✓	✓				✓
Soil erosion (global soil erosion by water, Mg/ha/year)	(Borrelli et al., 2020)			✓	✓		
Aridity (global aridity index, average annual temperature (°C), potential evapotranspiration (mm))	(Fick & Hijmans, 2017; Trabucco & Zomer, 2009; Zomer et al., 2008)	✓	✓	✓	✓		
Irrigation water availability (average groundwater table depth (cm), river volume (million m^3))	(Fan et al., 2013; Lehner & Grill, 2013; Linke et al., 2019)		✓				
Crop type (crop irrigation system	(International Food Policy Research	✓	✓				

suitability and irrigation dependency)	Institute, 2019; Portmann et al., 2010)						
Access to irrigation (percentage area equipped with irrigation)	(Siebert et al., 2013)					✓	✓
Poverty (percentage of people living in poverty outside of urban centers)	(Elvidge et al., 2009) (CIESIN/IFPRI/CIAT, 2011)	✓	✓	✓	✓	✓	✓
Access to knowledge and equipment (market accessibility index)	(Verburg et al., 2011)	✓		✓	✓	✓	✓
Farm size (dominant field size)	(Lesiv et al., 2019)	✓	✓	✓	✓	✓	✓
Land ownership (ease of registering property at national level)	(World Bank, 2020)	✓	✓				

5.2.3. Identifying spatial (mis)matches between climate impacts and adaptation suitability

Areas showing a decline in crop climate suitability and/or highest concurrent worsening of climate extremes were identified as the most adversely affected areas by climate change. Within these areas, we quantified the extent to which harvested hectares for our selected crop productions matched regions with no potential, low potential, or high potential to implement each of the adaptations. We defined low potential areas as areas with adaptation potential index scores <= 0.5, high potential areas as areas with adaptation potential index scores >0.5, and areas of no potential as areas where exclusion factors are present, and no potential suitability was therefore mapped. Additionally, we considered all areas with adaptation potential index scores >0.1 as areas of "tangible" potential. Due to a lack of data availability for some of the adaptations, our evaluation of spatial (mis-)matches does not take into consideration the extent to which some adaptations may or may not already be implemented in certain areas.

5.3. Results

5.3.1. Climate change impacts on crop producing regions of the Mediterranean Basin

Our analysis reveals high-end climate change will have varying, yet substantial effects on all our selected crops. The most adverse impacts in terms of declining suitability and/or highest increases in heat stress days and maximum consecutive dry days are found for cotton, sunflower, olive, and wheat (**Table 5.3**), where they are projected to affect at least half of harvested areas. Grape is the least adversely affected crop (24% of harvested areas are projected to be affected by the most adverse impacts), due to its production occurring primarily on the north-western perimeter of the Mediterranean ecoregion where more modest drying and warming is forecast (**Figure 5.2**). Declining suitability occurs largely within areas also witnessing the highest increases in the duration and/or frequency of drought and heat stress respectively. Yet, areas affected by the most substantial increases in heat stress days and the maximum number of consecutive dry days and far exceed areas projected to witness declining overall climatic suitability. Additionally, the climate suitability analysis revealed that important crops for the Mediterranean region, in particular citrus and cotton, are currently being cultivated outside of their suitable climatic niches. This result indicates that farm-based adaptations are likely to already have been deployed within the respective production areas to make the production of these crops possible.

Table 5.3 – Total harvested crop areas and share of crop areas expected to undergo declining climatic suitability and/or expected to witness highest regional increases in the frequency and/or duration of heat stress (WSDI) and drought (CDD) (2nd and 3rd tertiles) across the Mediterranean Basin (2041-2070 period vs. 1981-2010 period). *Cotton, orange, and mandarin are currently being cultivated in the region entirely outside the climatic suitability niche foreseen by Ecocrop, the model therefore does not quantify any further declines in suitability for these crops.

	Total harvested crop area (ha)	Share of harvested area subject to declining climatic suitability (%)	Share of harvested area affected by highest increases in maximum CDD and WSDI (%)	Share of harvested area subject to declining climatic suitability and/or affected by highest increases in maximum CDD and WSDI (%)
Wheat (assuming all common)	17’603’393	10.6	49	52
Wheat (assuming all durum)	17’603’393	5.6	49	50
Olive	6’212’088	4.8	48	50
Grape	2’988’617	0.3	24	24
Sunflower	1’397’177	12.3	51	52
Cotton	968’818	0*	57	57
Tomato	570’122	0.7	43	43
Orange	485’400	0*	44	44
Mandarin / tangerine / clementine	236’151	0*	43	43

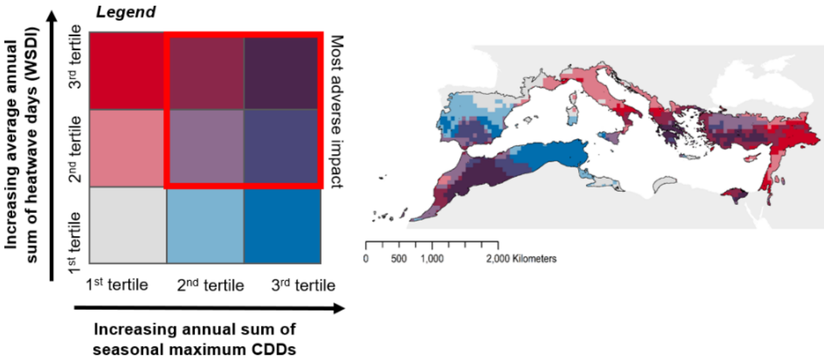

Figure 5.2 – Mediterranean areas forecast to witness increasing maximum CDD and WSDI under climate change, partitioned in tertiles. Areas subject to increases belonging to at least the 2nd tertile in both indicators were selected to define regions with potential for the most adverse climate change impacts, alongside areas subject to declining crop suitability.

5.3.2. Spatial (mis)matches between adaptation potential and needs in Mediterranean croplands

Overall, the most adverse climate change impacts are expected along the south-western and eastern rims of the Mediterranean Basin, potentially affecting an estimated 48% of harvested areas (**Figure 5.2**). Different types of adaptation have different potential suitability for implementation within these regions (**Figure 5.3**). Soil-based adaptations (reduced tillage and conservation agriculture) have the most widespread potential applicability, having the ability to be implemented on all cropland area. However, only 34% of most affected croplands are estimated to have high potential applicability for reduced tillage, and 21% are estimated to have high potential applicability for conservation agriculture. The remaining adaptations have considerably lower potential. Drip irrigation is only applicable to 10% of the most adversely impacted areas (including both high and low potential areas), as rain-fed areas are most affected by climate change. Despite the broad scope for irrigation expansion, this adaptation has the lowest share of land under high potential applicability when compared to all other adaptations, corresponding to only 1% of most affected rain-fed areas. Variety and crop change have an overall greater yet still limited scope for implementation, respectively estimated at 26 and 36% of most adversely affected areas when considering both low and high potential areas.

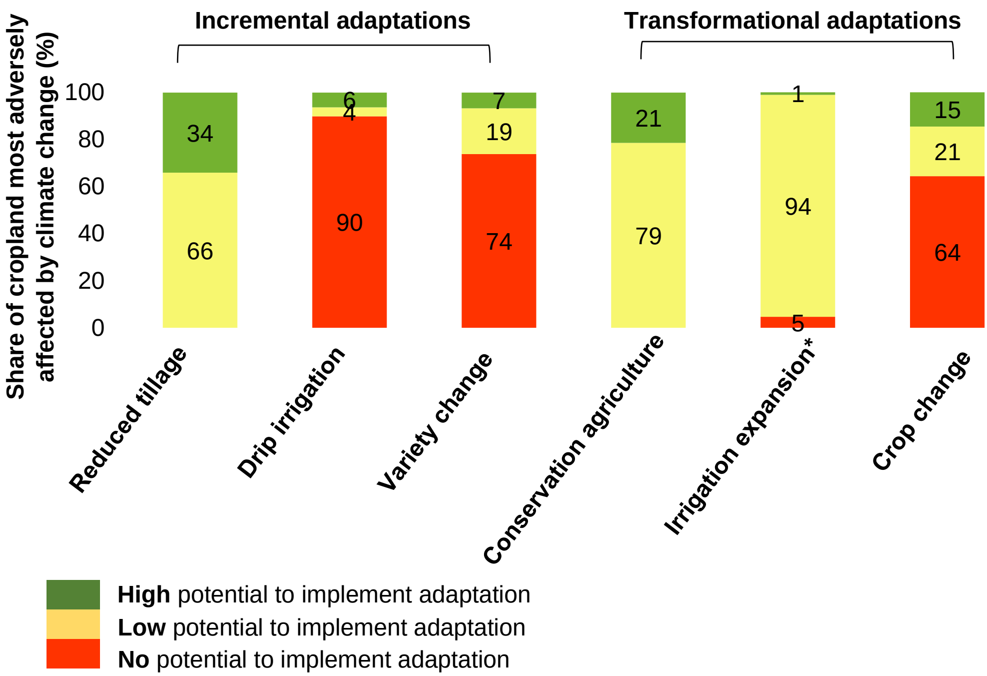

Figure 5.3 – Share (%) of Mediterranean cropland area forecast to be most adversely affected by climate change (i.e., by declining climatic suitability and/or highest increased duration or occurrence of extremes, corresponding to 48% of total cropland area) with no potential, low potential, or high potential to implement each farm-based adaptation. *Share of potential implementation for irrigation expansion was calculated only for predominantly rain-fed areas, unlike the other adaptations which were evaluated across all croplands.

Disaggregating results to representative crops reveals that reduced tillage and conservation agriculture have the most widespread high potential applicability within affected areas under cultivation of citrus crops (averaging 47% applicability in worst impact areas), and the lowest shares for grape, olive, and sunflower (averaging 31%) (**Table 5.4**). Drip irrigation is also mostly suitable to highly affected areas under cultivation of citrus crops, while other crops see applicability only apply to <50% of their most affected areas, with particularly low shares for grape, olive, and sunflower (while for wheat no application is possible). Irrigation expansion sees the least variation in applicability amongst the different crops, with minor favourability for cotton where 6% of highly affected rainfed areas have high potential for expansion. Variety change seems to only present a widespread potential adaptation option for olive production, where it is applicable to 81% of its most impacted harvested areas, while crop change is particularly applicable to citrus crops and grape, with all other crops seeing applicability within half of their highly affected areas or less. The crop-specific analysis therefore does not suggest that the most adversely affected crops also have a greater potential to implement adaptations.

Table 5.4 – Shares (%) of Mediterranean crop areas forecast to be most adversely affected by climate change (i.e., by declining climatic suitability and/or highest increased duration or occurrence of extremes) with no potential, low potential, or high potential to implement each farm-based adaptation. *Share of potential implementation for irrigation expansion was calculated only for predominantly rain-fed areas, unlike the other adaptations which were evaluated across all croplands.

		Incremental adaptations			Transformational adaptations		
	Potential to implement adaptations	Reduced tillage	Drip irrigation	Variety change	Conservation agriculture	Irrigation expansion*	Crop change
Wheat (assuming all common)	None	0	100	85	0	3	51
	Low	65	0	9	77	96	33
	High	35	0	5	23	1	16
Wheat (assuming all durum)	None	0	100	91	0	4	50
	Low	66	0	7	78	96	26
	High	34	0	2	22	1	24
Olive	None	0	75	19	0	8	100
	Low	70	11	62	84	91	0
	High	30	15	19	16	1	0
Grape	None	0	86	84	0	6	38
	Low	70	7	12	81	94	31
	High	30	8	4	19	0	31

Sunflower	None	0	99	88	0	3	99
	Low	68	0	11	81	94	1
	High	32	1	2	19	3	0
Cotton	None	0	58	100	0	6	100
	Low	57	12	0	70	89	0
	High	43	30	0	30	6	0
Tomato	None	0	56	93	0	6	58
	Low	60	14	6	71	94	23
	High	40	31	1	29	0	19
Orange	None	0	28	100	0	6	45
	Low	51	23	0	65	94	30
	High	49	48	0	35	1	25
Mandarin / tangerine / clementine	None	0	30	100	0	4	40
	Low	55	25	0	69	96	32
	High	45	45	0	31	1	28

Areas most adversely affected by climate change see less than half of their land match areas of current tangible potential for adaptation (i.e., with adaptation potential index values >0.1) in most countries in the Mediterranean region (SI). In the Mediterranean extents of Montenegro, Bosnia and Herzegovina, Slovenia, Turkey, Portugal, Jordan, Morocco, Tunisia, Greece, Libya, and Albania, the average spatial mismatches are especially high (>60%). This finding is particularly relevant for Morocco, Greece, Turkey, and Bosnia and Herzegovina, as over 30% of their Mediterranean harvested areas are in regions projected to witness the most adverse climatic impacts. For these countries, our results reveal that reduced tillage and crop changes represent the most suitable tangible adaptation options (on average suitable on 87% and 37% of most affected areas respectively). Drip irrigation represents a relatively more viable option in Greece and Morocco than in the other countries, while the (albeit small) Mediterranean extent of Bosnia and Herzegovina has high potential for irrigation expansion and variety change where most needed. Egypt, Spain, and Israel are the remaining countries with highest (>30%) shares of cropland projected to witness the most adverse climate change impacts. In these countries, however, greater tangible capacity for adaptation is primarily due to high potentials for drip irrigation, conservation agriculture, and crop change (**SI**). Overall, transformational adaptations seem to have lower potential for implementation than incremental adaptations, while also having a stronger negative correlation with most adversely affected areas from drought and heat stress (**Figures 5.4, 5.5**). The socio-economic adoption factors primarily leading this latter trend are tied to the distribution of current irrigated crop productions, land ownership, market accessibility, and poverty, all showing negative correlation values (r_s) respectively ranging from *-.20* to *-.15 (p<0.01)*.

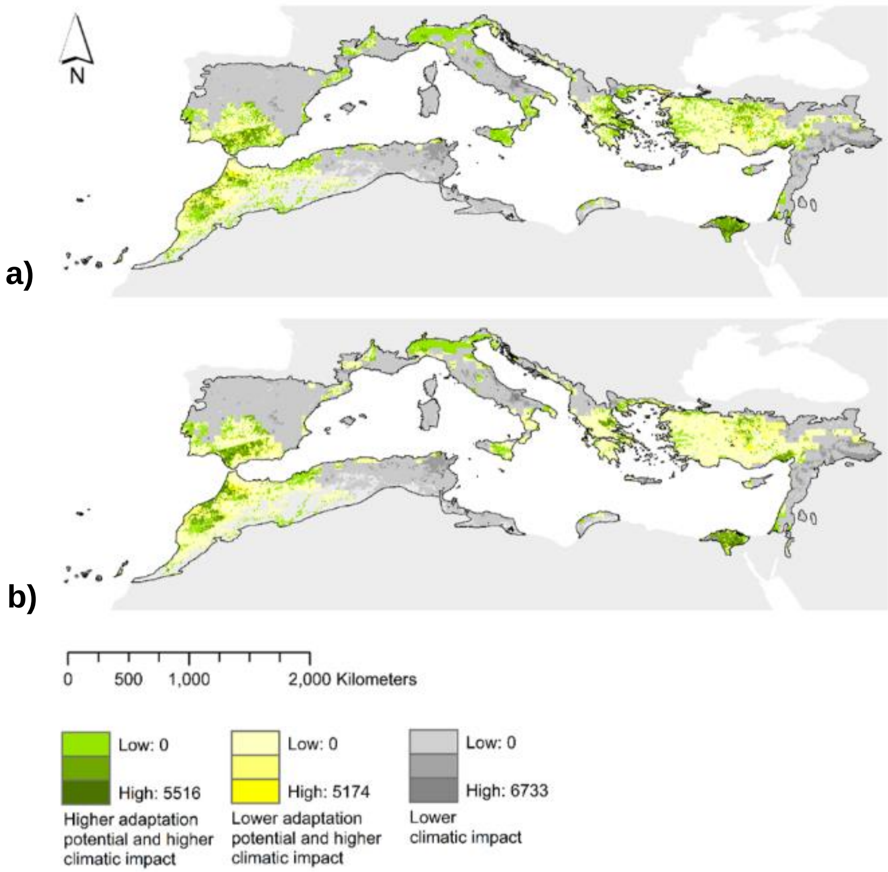

Figure 5.4 – Extent of Mediterranean cropland areas (ha) forecast to be least and most adversely affected by climate change and to match areas with high or low potential to implement (a) incremental adaptations, or (b) transformational adaptations. The highest adaptation potential index value from any respective adaptation was selected for each pixel to determine whether overall adaptation potential was high or low.

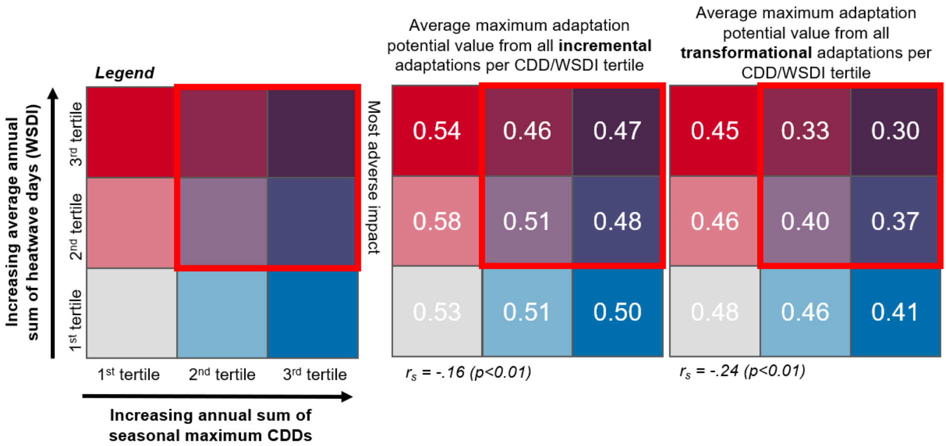

Figure 5.5 – Average maximum potential to implement incremental adaptations or transformational adaptations within regions corresponding to each intersecting CDD/WSDI change tertile. Spearman's rank correlation (r_s) values between average highest adaptation potential and intersecting tertile combination for the two climatic extremes are additionally illustrated. The maximum value for the maximum CDD index corresponds to a 33-day increase, while the maximum value for the WSDI index corresponds to a 124-day increase.

5.4. Discussion

5.4.1. Implications of results

This study reveals that all crop producing regions of the Mediterranean Basin will be subject to increased climatic pressure from drought and heat stress, with Mediterranean cropland areas in Morocco, Greece, Turkey, and Bosnia and Herzegovina facing the most significant challenges due to more widespread climatic impacts and a greater mismatch between adaptation potential and needs. The identified regional worsening of both dry and hot extremes has similarly been recognized by past research (Lionello & Scarascia, 2020; Molina et al., 2020), including studies making use of data from the recent Coupled Model Intercomparison Project (CMIP6) (Ajjur & Al-Ghamdi, 2021; Liu et al., 2021; Vogel et al., 2020). Our results indicate that the extent of cropland area subject to increases in the duration or frequency of extremes will far exceed areas where shifting average climatic conditions will result in declining crop suitability, highlighting the importance of accounting for both conditions (Moriondo et al., 2011).

Amongst the most adversely affected countries with the greatest spatial mismatches between tangible adaptation potential and needs (Bosnia and Herzegovina, Greece, Morocco, and Turkey), recent estimates indicate that only between 0-14% of respective cropland areas are already under reduced tillage management (EUROSTAT, 2020; Kassam et al., 2019), and between 3 and 25% of irrigated areas are currently under drip irrigation (Jägermeyr et al., 2015). Reduced tillage represents the adaptation with the most widespread tangible potential for implementation in these countries, applicable, on average, to 87% of most affected cropland areas, thereby revealing vast opportunity to expand the practice. In Morocco, the national Green Plan may contribute to bridging this potential by striving to attain sustainable agricultural intensification and modernization in part by subsidizing reduced tillage and conservation agriculture (i.e., via the low-cost provisioning of direct seeders) and by partnering with research organization to fund demonstration areas and research on crop varieties suited to the practice (ICARDA, 2021; Izzi, 2013; Mrabet et al., 2012). These efforts (particularly access to subsidies) have however thus far struggled to reach smaller farmers lacking funds and land titles (Asedrem, 2021). According to our analysis, these farmers are precisely those most likely to face the greatest increases in the frequency or duration of drought and heat stress, and thus to face greater vulnerability. Similar action points for the implementation of soil-based adaptations can be found in Turkey, Greece, and Bosnia and Herzegovina, with studies placing value particularly on the importance of access to low-cost machinery (with successful results in Turkey where direct seeders are locally produced), and increased knowledge exchange (Altikat et al., 2018; Kassam et al., 2019; Lithourgidis et al., 2009; Žurovec & Vedeld, 2019).

In these same countries facing the greatest adaptation challenges, the remaining water- and crop-based adaptations are estimated to provide more limited potentials for implementation within worst affected areas. In Morocco, relatively more widespread tangible potentials are found for drip irrigation (29% spatial match) and crop change (68% spatial match). Our analysis reveals that crop transitions in this context primarily concern substitutions by olives or dates (largely of wheat). Here too, the Green Morocco Plan has already been promoting this transition by incentivizing fruit orchards (especially olives) over cereal production in a bid to increase the competitiveness of the agricultural sector (Asedrem, 2021). Within areas already equipped with irrigation, this transition is likely to increase the potential for drip irrigation beyond our current estimate, presently constrained in part by the high share of wheat production in the country. While similar tangible adaptation potentials are found for crop change and drip irrigation in Greece, the country sees greater opportunity for irrigation expansion (25% spatial match), and variety change (21% spatial match). Past research has advocated for irrigation expansion in the country to focus on public on-demand pressurized networks to improve distributional efficiency and equity (Latinopoulos, 2005), while the high levels of genetic and phenotypic variety for olive present in Greece show promise for the feasibility of variety change (Banilas et al., 2009). The same opportunities apply to Bosnia and Herzegovina where particularly irrigation expansion has thus far been considerably less explored, while variety change potential in this context concerns tomatoes and wheat (Dodig et al., 2012; The World Bank, 2021). In Turkey, tangible adaptation potentials for water- and crop-based adaptations all fall in the range of 13-25%, as vast agricultural areas situated in the country's southern Mediterranean bioregion witness unfavorable socio-economic and biophysical conditions for adaptation.

The identification of countries where greater matches between climate impact and adaptation potential or realization can be found may contribute to the identification of processes alongside conditions leading to adaptation. In Israel, 48% of highly impacted cropland was found to have tangible adaptation potentials on average, with a 47% overall spatial match for drip irrigation. This potential looks likely to have already largely been realized, as drip irrigation is present on 74% of irrigated cropland in the country following widespread investments since the 1960's (Jägermeyr et al., 2015; Molle & Sanchis-Ibor, 2019). In Egypt, where tangible drip irrigation potentials showed an even higher spatial match of 73%, adoption rates are on the contrary very low (7% of irrigated area utilizes drip) (Jägermeyr et al., 2015).

Positive forecasts across the country have placed emphasis on policy restrictions on flood irrigation, increased presence of extension agents, and knowledge exchange following the practice's demonstrable returns on investment (Ali et al., 2020; Mourshed, 1996). Similarly, the considerable, yet as-of-yet unrealized, potential for conservation agriculture in either country may be able to draw on lessons from Syria, Jordan, and Iraq – regions where the practice has successfully been implemented and where the presence of similar rain-fed and irrigated systems can provide a blueprint for further implementation and scaling (Loss et al., 2015).

A reflection on adaptation process is relevant as the structural and physical adaptations explored in this study can be brought about through both "soft-path" and "hard-path" approaches. Examples include promoting small-scale water collection techniques and the farming of local crop species and landraces, vs. favoring water harvesting through large reservoirs and implementing varietal change through novel genetic breeding (Fraser et al., 2016; Rosa et al., 2020). These different approaches will encompass different processes catalyzed by diverging actors, agencies, technologies, and scales, and will thereby see the ultimate implementation of the adaptations hinge on different leverage points (Mockshell & Kamanda, 2018). Importantly, they will furthermore result in different synergies and tradeoffs with social-ecological factors. Exploring the "how" behind the implementation of our explored adaptations is therefore crucial to avoid maladaptive outcomes and vulnerability transfers (Barreteau et al., 2020).

Alongside identifying areas where the deployment of adaptations is needed and possible, this research additionally identified areas where, conversely, spatial mismatches appear more probable. Particularly low potentials are seen for adaptations rendered more vulnerable by climate change. The potentials for irrigation expansion are especially constrained by future, limited, water availability in the region (Rosa et al., 2020). This finding therefore suggests that one of the most frequently implemented adaptation strategies in the region might become increasingly less prominent in the future (Harmanny & Malek, 2019). Similarly, higher heat and drought tolerance under new crops and varieties is in some regions not enough to achieve suitable climatic conditions under climate change. The lower overall potential of transformational adaptations within regions witnessing the most adverse risks from climate change is concerning. Although these adaptations are deemed to have higher costs, they also have greater potential to maintain productivity under climate stress. Conservation agriculture and irrigation expansion (albeit applicable to different areas) both result in greater changes to soil water content than the implementation of reduced tillage or drip irrigation (Palm et al., 2014), while crop changes, by more comprehensively altering input management, can provide greater opportunities to insure against increased drought and heat stress.

These transformational adaptations are often conceptualized as a "last step" in the adaptations ladder (Rippke et al., 2016; Wezel et al., 2014). Their low potential applicability throughout a majority of worst affected areas throughout the Mediterranean Basin (88% of worst affected areas have low or no applicability on average) suggests the identification of potential limits to adaptation, i.e., points at which "an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive action" (Klein et al., 2015). The existence of limits to adaptation within agricultural systems of the Mediterranean was, amongst others, identified by Iglesias et al. (2011), which stipulated that agricultural systems once suited to the region are now no longer adapted to its conditions. Yet, little progress (globally) has since been made within adaptation research to identify and engage with potential limits (Berrang-Ford et al., 2021; Thomas et al., 2021). Identifying actor-centered social or physical limits to adaptation is however critical to quantify eventual needs for more transformational approaches (e.g., involving a change in livelihood or relocation of farming activities, as proposed by other conceptualizations of transformational adaptation (Panda, 2018)), and the eventual losses and gains tied to these changes, so that preparatory action may be taken (Dow et al., 2013).

5.4.2. Methodological limitations

In this research, we implemented a "broad-brush" approach toward the identification of spatial (mis)matches between areas most adversely impacted by climate change and areas with greater potential to implement farm-based adaptations. We therefore simplified and synthesized complex biophysical and social processes, as we relied on secondary data and indicators when mapping climatic impacts and adaptation potentials. The results are for example subject to uncertainties related to the reliability of climatic Global Circulation models, particularly when considering the location of extremes (Knutti & Sedláček, 2013). Furthermore, we did not make use of the latest CMIP6 data, yet comparisons with CMIP5 simulations confirm warming and drying across the region, with even stronger warming projected under CMIP6 (Cos Espuña, 2021). The chosen indicators for drought and heat stress additionally have their own shortcomings, as CDD is an indicator of meteorological, rather than agricultural drought, and WSDI does not quantify heat wave intensity, only duration (Molina et al., 2020). Additionally, both indicators can merely point toward areas at potential risk of declining agricultural production and cannot directly inform predictions on yield declines. Nevertheless, the two indicators are amongst the most widely used for drought and heat stress, enabling comparison with other assessments (ECMWF, 2019). An improved (and more realistic) representation of agricultural impacts would require the deployment of (an ensemble of) locally calibrated crop growth models (e.g., Rosenzweig et al. (2014)) capable of capturing the temporal sensitivities of specific crop growth stages to changing average and extreme climatic conditions, alongside influences from CO_2 fertilization and indirect climatic effects (SI). Despite not quantifying changes to crop yields, agreement was nonetheless found between our study's identification of areas at greatest risk from adverse climatic impact, and areas forecast to undergo declining productivity by crop yield modelling studies (Blanco-Ward et al., 2017; Fraga et al., 2020; Li et al., 2021; Moriondo et al., 2011; Semenov & Shewry, 2011), with CO_2 fertilization partially or fully mitigating yield losses for some productions (Jägermeyr et al., 2021; Li et al., 2021).

The mapping of our selected farm-based adaptation potentials aimed to offer an anticipatory perspective and was therefore based on "present-day" biophysical and socio-economic proxies representing constraints or enablers to each adaptation. A major shortcoming of this methodological approach is tied to a lack of (up to date) spatial data for several identified adoption factors, particularly for those addressing institutional and socio-economic influences. These include the presence of farmer and stakeholder networks which work to demonstrate adaptation benefits and provide opportunities for knowledge exchange. These networks were identified as a significant driver for most of the explored adaptations (SI). Similar cross-cutting yet omitted adoption factors referred to the presence of subsidy or incentive programs (e.g., promoting the adoption of conservation agriculture (Kassam et al., 2012)), as well as the role of farmer risk attitudes and traditionalist preferences which may advance or hinder the adoption of new practices and approaches (e.g., resistance to the adoption of drip irrigation in Spain (Molle & Sanchis-Ibor, 2019)) (SI). Secondly, by comparing present day adaptation potentials with areas of future climatic impact, our approach fails to consider that many (particularly social) adoption factors are highly dynamic while also not holding uniform nor equal weighting. Therefore, while our identified thresholds demarcating baseline adoption index values might currently be high, these may be lower in the future, for example following policy shifts, declining investment costs from increased technology supply, or following the attainment of a critical mass of early adopters (Otto et al., 2020). The adoption index values presented in our analysis would also likely have shown greater potentials if scenarios implementing multiple adaptations simultaneously would have been explored (e.g., combining substitution of cereal crops with potential to implement drip irrigation). Ultimately, whether the adaptation potentials identified in this study translate to successful implementations transcends the presence of socio-economic or biophysical conditions and calls for a more detailed reflection on the adaptation process and of associated implications (e.g., influence of crop transitions on heritage landscapes, water consumption, food security, and trade (Fader et al., 2016)).

Despite the varied range of studied technical and physical farm-based adaptations, this research nevertheless presents a partial view of adaptation options available to farmers and land managers across the Mediterranean (Harmanny & Malek, 2019) (SI), for example by disregarding social or financial avenues. Within the range of technical and physical adaptations that were explored, we furthermore did not consider the important potential behind farm diversification approaches, from intercropping practices to integrated silvo-pastoral systems (Aguilera et al., 2020). Investigating a more comprehensive set of adaptations would require addressing both finer and wider (tele-connected) scales than the one implemented in this analysis. Our regional scale work can however complement and inform such studies, spanning from integrated crop modelling research quantifying yield effects under more comprehensive adaptation scenarios, to place-based investigations exploring social limits to adaptations and novel transformation potentials (Chaplin-Kramer et al., 2021).

5.5. Conclusion

Severe warming and drying across the Mediterranean Basin under a high-end climate change scenario is likely to have extensive repercussions on the region's agricultural sector. 48% of areas under production of grape, olive, citrus, cotton, tomato, sunflower, and wheat are expected to face a significant worsening of drought and heatwaves, alongside declining climatic suitability. We demonstrate that there is great variation in the potential to implement farm-based adaptations in the region. More widespread tangible potentials within the likely worst affected countries are on average found for crop changes and the implementation of reduced tillage, while potentials for irrigation expansion and variety change are particularly low. Overall, regions exposed to greater climatic impact, concentrated along the south-western and eastern rims of the region, are likely to have a lower potential for adaptation. Importantly, transformational adaptations, i.e., the adaptations with the greatest hypothesized capacity to buffer against the effects of climate change, have particularly low potentials in regions where the most adverse climate change impacts are anticipated. For regions where considerable adaptation capacity and low levels of present-day implementation were identified, further studies should seek to investigate how adaptation capacity has differed from adaptation preparedness, and through which processes higher levels of adaptation may be realized. For regions where a nearing of adaptation limits has been theorized, future consideration for more transformational options, and the sacrifices and opportunities these entail, is necessary.

Acknowledgements

This research was supported by the European Union's Horizon 2020 Research and Innovation Program through the project CONSOLE (grant agreement 817949), and by the 2017-2018 Belmont Forum and BiodivERsA joint call for research proposals under the BiodivScen ERA-Net COFUND programme (funding organizations: Dutch National Research Council NWO (grant E10005) and Agence Nationale pour la Recherce (FutureWeb ANR-18-EBI4-00009)). This work does not necessarily reflect the views of the European Union and in no way anticipates the Commission's future policy. We would like to acknowledge the World Climate Programme's Working Group on Coupled Modelling alongside the climate modelling groups referenced in section 5.2.1 for producing and providing access to the CMIP climate data. We would furthermore like to thank J. Appelt for helpful discussions on crop climate suitability modelling.

Chapter 6

Synthesis

Chapter 6 – Synthesis

6.1. Revisiting the research questions

This thesis sought to draw on the methodological and organizational principles of SES complexity to explore possible futures for Mediterranean agricultural landscapes. It approached this research aim by investigating (1) which farm-level drivers, actors, and feedbacks are shaping adaptations in Mediterranean agricultural landscapes, and (2) which implementation pathways can successfully deliver on the adaptation's intended goals. This work was addressed by implementing a mixed-method and multi-scalar approach drawing on insights from published literature, stakeholder interviews, spatial analysis, or agent-based modelling within sub-national case study sites as well as across the whole of the Mediterranean Basin. In this final synthesis chapter, I will discuss how the research presented in this thesis contributes to answering the two core research questions and will reflect on both the methodological and societal relevance of the respective findings.

6.2. Farm-scale drivers, actors, and feedbacks shaping adaptations in Mediterranean agricultural landscapes

Addressing the (spatial) characterization of agricultural landscape change arising from farm-level action required the investigation of the core elements of multi-level change, i.e., the drivers, actors, and feedbacks which shape both the implementation and outcomes of adaptation (Hersperger et al., 2010). Each chapter addressed a case study where a different, archetypal regional adaptation pathway prevails. According to the conceptualization presented by Moragues-Faus, Ortiz-Miranda and Marsden (2013), current pathways can be distinguished based on their pursuit of farm modernization vs. diversification of agricultural, or non-agricultural on- or off-farm income streams. While Chapters 2 and 3 investigated an agricultural context where gradual disinvestment from agriculture prevails (i.e., farmers increasingly rely on off-farm income), Chapter 4 focused on a case study where farmers are particularly inclined to engage in on-farm income diversification, and Chapter 5 solely sought to explore adaptations reflecting the productivist and "modern" adaptation pathway. Following the analysis of peer-reviewed literature and (qualitative) stakeholder consultation, several farm-level adaptations were explored as characteristic of the different pathways (**Table 6.1**). The works of Kizos and Koulouri (2010) (relevant to Ch. 2, 3), Rivaroli et al. (2017) (Ch. 4), and Harmanny and Malek (2019) (Ch. 5) were particularly instrumental in selecting these prevalent adaptations of direct influence to broader landscape changes in each case study area.

Table 6.1 – Explored farm-level adaptations in this thesis consistent with each of the prevalent adaptation pathways across the Mediterranean region.

Adaptation pathway	Adaptive action	Chapter(s)
Modernization (productivism)	Expand land area	2, 3, 4
	Intensify management	2, 3, 4, 5
	Conserve soil resources	5
	Change to higher value crop / variety	2, 4, 5
On-farm agricultural diversification	Increase value of agricultural produce	2, 4
On-farm non-agricultural income diversification	Invest in agri-tourism	2, 4
Off-farm income diversification	Sell land	2, 3, 4
	Abandon land	2, 3
	De-intensify management	2, 3

This thesis conceptualized the farm/farmer as the primary unit of analysis for explaining the causal mechanisms behind landscape transitions. The exploration of "actors" was therefore centered on the construction of farmer typologies which could synthesize the internal attributes determining engagement with different adaptation pathways (Guarín et al., 2020). This ambition required the typologies to capture a rich diversity of attributes based on elements of both farming ability and willingness (Valbuena et al., 2010), challenging the more homogeneous and simplistic farmer representations which have problematically informed agricultural policy design, including across the European Union (Brown et al., 2021). In this context, attributes defining farmer willingness have especially been overlooked (Brown et al., 2021). These attributes are defined as farmer values and intentions (i.e., goals) which define preferences for certain adaptations (Mills et al., 2017; Valbuena et al., 2010).

A first dimension of farmer willingness identified and explored in this thesis addressed farmers' economic goals in relation to agricultural activities. In both the case studies of Lesvos (Greece) and Romagna (Italy), farmers held diverging economic objectives, as some opted for satisficing approaches and thus chose not to maximize profits and engage in adaptive actions yielding the greatest economic returns. A second dimension recognized preferences for different farming "lifestyles" (van der Ploeg & Roep, 2003), or adaptation pathways (productivist vs. diversifying), as farmers displayed path-dependencies and repeated engagement in a cohesive set of preferred adaptations. A final dimension, instead, addressed a willingness to engage in actions which align with a farmer's own underlying values and attitudes. Chapter 4 explored farmers valuing autonomy or environmental stewardship as respectively inclined to engage in agricultural income diversification through novel supply chains involving direct sale or the certification of sustainable production. In Chapters 2 and 3, farmers were found to value their olive plantations as entrepreneurial (productive) endeavors and/or as the preservation of family heritage, mirroring a widespread perspective among farmers in the Mediterranean Basin (Debolini et al., 2018). This latter value was associated with a reluctance to sell the plantations, and therefore to (1) continue their maintenance even under unprofitable circumstances through part-time engagement, (2) to witness their abandonment upon full retirement if no willing successors are present, or (3) to engage in agricultural income diversification by joining cooperatives aiming to valorize local produce through its traditionality. In addition to influencing a preferred pathway, farmer attitudes and values were furthermore found to play a role in determining a general willingness to transform their systems (farmers valuing openness to change or with high concern for climate change, Chapters 3, 4, and 5) or favor specific adaptive actions within pathways (farmers concerned about water conservation favored changing their production to less water demanding crops, or to invest in efficient irrigation systems, Ch. 4).

Attributes characterizing farmer ability across the case study areas were more numerous than those characterizing willingness, perhaps due to their greater prior characterization and tangibility (Mills et al., 2017). Commonalities were found in the influential role played by greater farm size, wealth, and management intensity in generating positive feedbacks and thus repeated engagement in a productivist pathway. In the sub-national case study regions, attributes of farmer age, presence of successorship, full-time engagement in farming, and cooperative membership were all investigated as contributors to decisions on whether to maintain current system properties or engage in system change. Older farmers without successors were most likely to maintain their systems and not undertake adaptive action (Ch. 3, 4), while younger farmers (in Ch. 3) held a greater inclination to either engage in productivist action or seek partial or full off-farm employment. Cooperative membership granted farmers access to financing mechanisms and knowledge resources and was linked with productivist actions of increased (irrigation) intensity (Ch. 3, 4). Specific crop types and land ownership (Ch. 4, 5) similarly enabled greater input intensity with regards to irrigation. Altogether, the explored attributes characterizing farmer ability and willingness exemplify some of the significant diversity in farming systems present within the Mediterranean Basin.

The characterization of external drivers worked to identify if and how present policy mechanisms or discourses are engaging with attributes of farming ability and willingness to steer adaptation processes. In Chapters 2 and 3, the primary influence of policy was identified in area-based income support subsidies to farmers (the current "Basic Payment Scheme" of the European Union's Common Agricultural Policy). This subsidy's goal is to ensure some income stability to farmers; it is largely uniform and not tailored to support specific (disadvantaged) farming types. Its direct consequence, in a traditional small-holder farming context, is primarily to allow some low-income earning farmers to maintain viability and incentivize top-earners to invest in area expansion (Kazukauskas et al., 2013). The limited influence of such policy was explicitly expressed in farmer interviews, which deemed it to be less influential than other factors affecting farmer wealth, notably olive oil prices and changing costs of production. Chapter 4 instead identified greater reliance by farmers on the voluntary financing components of the Union's agricultural policy broadly addressing rural development and action on environment and climate goals. These voluntary mechanisms were found to incentivize on-farm diversification trajectories (e.g., by subsidizing uptake of organic farming or agri-tourism investments). Additionally, Chapter 4 explored the role of policy beyond agricultural income-support by investigating water policy perspectives in a drought-prone region. Solely applying policy incentives targeting increased irrigation provisioning will have the primary effect of successfully reducing some drought damage, yet by consequence may also result in long-term vulnerability by incentivizing transitions to water demanding crops while initially reducing risk perceptions and thus willingness to engage in further adaptive behavior (as similarly identified in France by Bergeret & Lavorel (2022)). Water policy discourses addressing the regulation of irrigation demand were instead found to include a broader range of initiatives, from active norm engagement (promoting generic drought adaptation behavior) to constraints on the production of water intensive crops. These demand policies demonstrate more tailored approaches promoting lower-intensity and resilient farming, yet also exemplify potential lack of coherence by simultaneously incentivizing generic adaptation behavior.

Further external determinants of farm income were investigated as drivers of specific adaptation pathways. Higher olive oil prices were associated with the expansion of farmed plantations and more intense management, while increased labor wages were linked to more farmers disengaging from farm work (Ch. 3). Climate variables were explicitly explored in Chapters 4 and 5, where anticipated or experienced climate change impacts were conceptualized as driving decisions to engage in (any) adaptation and to particularly favor transformative, water sparing or harvesting actions. Farmers were furthermore found to adapt to biophysical factors determining poor farming conditions and accessibility (e.g., poor soils, sloping terrain, lack of irrigation) by either engaging in corrective productivist action (e.g., irrigation expansion, soil conservation measures), or by ceasing farming activities on these unproductive/high-cost fields. Social factors, identified in the presence of farmer cooperatives (whether socially oriented or "traditional"), and neighborhood dynamics were furthermore found to influence adaptation decisions, respectively by shaping productivist or diversified trajectories and by influencing subjective norms to reinforce prevailing pathways (Ch. 2, 3, 4).

Direct relations between external drivers and farmer attitudes and values were thus addressed in this thesis and grounded in empirical evidence, secondary literature, and behavioral theory. Experienced climatic impacts and active norm engagement policies influence farmer drought risk perceptions and consequently willingness to adapt, consistent with the Protection Motivation Theory (Grothmann & Patt, 2005) (Chapter 4). In Chapter 3, neighborhood dynamics shift subjective norms and farmer adaptation preferences, consistent with the Theory of Planned Behavior (Ajzen, 1991), and social cooperative membership promotes the development of cultural values among farmers (e.g., Barghusen et al. (2021)). These dynamics exemplify that drivers directly influence not just the state of farmer assets, but also their very goals and objectives, representing a "higher-order" feedback loop (Le et al., 2012). A second set of examples of such feedback loops is also explored in Chapters 3 and 4, where they are instead indirectly triggered by external drivers. This is investigated in both chapters by farmers choosing to engage in a novel adaptation pathway delineating their preferred actions (represented by changing "farmer type" in Chapter 3, and "farmer strategy" in Chapter 4). Farmers abruptly or gradually engage in a novel pathway following a recognized need to change their system (typically informed by declining farm revenues), and the identification of a financially attractive action which aligns with their values, attitudes, and asset constraints. The investigation of higher-order feedback loops is more rarely addressed by modelling studies (Le et al., 2012), yet capturing the drivers and consequences of shifting agent goals is crucial for investigating the transitions and transformations required to break free from unsustainable path-dependencies (Fazey et al., 2016).

6.3. Approaches to characterizing adaptation processes in Mediterranean agricultural landscapes for spatial futures explorations

This thesis' exploration of future landscape change processes deployed a spatialized mapping and modelling approach to account for geographical features and their disparate influences and outcomes. Two separate processes enabled the construction of the required spatial tools; a first process determined the identification and characterization of the elements of change (whose results are outlined in 6.2), while a second process was concerned with the spatial representation of the characterized elements. While common process-specific methods were utilized across the case studies, their respective spatial scales and behavioral diversities necessitated different levels of generalization and reliance on primary data collection (Smajgl et al., 2011).

Chapters 2 and 3, based on landscape change processes within the municipality of Gera (Greece), made use of extensive interviews with the local farmer population to closely base the characterization of elements (especially of farmer attributes) on revealed local dynamics. The design of the semi-structured interviews was guided by the framework developed by Valbuena et al. (2010), and thus aimed to capture aspects of both farming ability and willingness, and was informed by past literature from the case study region which has extensively addressed landscape change processes. These sources led to the inclusion of closed questions addressing specific attributes of ability emphasizing farm management intensity, household income streams, cooperative membership, and consultation sources. Willingness dimensions were recorded via agreement with statements on future intensions and focused on exploring willingness to maintain land under family ownership. These farmer attributes were used as input for a hierarchical cluster analysis to construct a farmer typology. The methodological strength of this statistical approach lies in the close representation of contextualized realities by allowing "the data to speak for itself", and by more realistically creating rich and fluid actor types which share some characteristics (Guarín et al., 2020). The construction of the farmer typology was instrumental to enabling the "up-scaling" of the surveyed sample to the full municipal farming population within a spatial agent-based modelling environment by providing type-specific attribute distributions (Smajgl et al., 2011).

The cluster analysis was subsequently used to derive likelihoods of different farmer types engaging in different adaptations and farmer type changes to enable the definition of behavioral rules for the spatial model. In both cases, the explored dynamics were not based on articulated causal mechanisms. In contrast, some causal mechanisms were explicitly (qualitatively) identified in the interviews and could directly be reproduced as decision-rules in a modelling environment (particularly when relating to attributes of farmer ability, e.g., effect of changing olive oil prices on farmer revenues). Others, relating to farmer willingness, in some instances required greater reliance on secondary literature or behavioral theory. In particular, the interviews explored relations between farmer willingness and adaptations but did not explicitly investigate what drivers may shape farmer willingness in the first place. The characterization of drivers also relied more extensively on literature addressing regionally-relevant dynamics than on the interview results in order to extract a more comprehensive picture of the decision-making context of the regional farmer population, which is more likely to be skewed by individual farmer responses (Polhill et al., 2010). A stakeholder workshop with both members of the local farmer population and landscape change experts was furthermore conducted in part to confirm some of the more uncertain revealed dynamics from the farmer interviews and secondary literature. These more uncertain aspects of the model were furthermore tested in a sensitivity analysis. The overall characterization approach therefore followed that of previous publications addressing landscape change processes by means of spatial agent-based modelling, where (1) multiple sources and iteration is used for validation (via triangulation) of the characterization, (2) rationale behind processes and decision rules is transparently documented and modelling is subject to sensitivity analysis, and (3) qualitative information complements the characterization of structural elements (Polhill et al., 2010; Schouten et al., 2014).

The second case study region of Romagna (Italy), addressed by Chapter 4, fundamentally implemented the same design principles. Some different approaches were however adopted to reflect the larger case study area, presenting more diversified farming systems and adaptation behaviors. The interview process relied on less structured and more in-depth interviews with fewer farmers, supplemented with diverse key informant interviews following a similar format. Greater emphasis was placed on existing modelling and theoretical frameworks to guide the characterization process. The Modelling Human Behavior framework developed by Schlüter et al. (2017) formed the basis of the characterization by guiding the identification and analysis of the types of feedbacks and relational elements which typically comprise actor-centered social-ecological system analysis. As with Chapters 2 and 3, the farmer and key informant interviews were used to both identify relevant farmer attributes and drivers (in this latter case also relying more significantly on key informants and on secondary policy documents for the identification of influential policy discourses), as well as the relational feedback components. The Theory of Basic Values (Schwartz, 2012) was used for the characterization of farmer values, while the Model of Private Proactive Adaptation to Climate Change of Grothmann and Patt (2005) guided the formulation of the cognitive decision-making process determining adaptive action. The farmer typology could in this case not rely on a quantitative cluster analysis. Instead, it was replaced by the reproduction of an established farm production typology (European Commission, 2017). These crop production types were used to stratify (and thus make use of) census information regarding the distribution of attributes of farming ability. The distribution of farming strategies across the spatialized farmer population was subsequently determined based on the interview results and their frequency across the different production types, while the distribution of farmer attitudes and values was based on their frequency across all strategy-crop production combinations – justified by regional literature suggesting crop production to be a core determinant of farming strategy (Rivaroli et al., 2017), and interview results revealing linkages between values and attitudes, and farming strategies.

In contrast to the previous case studies, the Mediterranean-wide spatial forecasting analysis conducted in Chapter 5 did not involve a dynamic process-based investigation, and instead explored where current adaptation-specific attributes of farming ability are present to enable future system resilience under climate change. Attributes of farmer willingness were conceptually defined as desires to transform farming systems or maintain their core properties in light of anticipated climate change impacts (following the framework of Rippke et al. (2016)), and were therefore reflected in the selection of adaptations, leading to the investigation of different scenarios exploring the implementation of transformational and non-transformational actions. Attributes defining farming ability were only selected for this mapping analysis if no ambiguity regarding their influence and direction was found across regional literature, and if respective spatial proxies could be identified. While this thesis' chapters addressing wider spatial scales present greater potential for comparability, they therefore also required a greater degree of abstraction and are thus subject to greater uncertainty. This is most evident in the dependency on secondary data availability, potentially resulting in the reproduction of biases by excluding perspectives from data-scarce contexts, and in the more frequent integration of conceptual frameworks requiring assumptions on causal mechanisms (Muelder & Filatova, 2018; Schlüter et al., 2017).

6.4. Pathways and conditions to alternative agricultural landscape futures in the Mediterranean Basin

The characterization of agricultural landscape change processes led to the identification of diverse farmer types and feedbacks to external drivers. This process on its own can inform policy design on likely policy barriers or enablers within varied farmer communities. Yet, the multiple identified feedback mechanisms suggest that fully anticipating the consequences of future policy changes requires a dynamic exploration capable of accounting for their cumulative impacts. This future-oriented assessment presents a focal point of this thesis' second and final set of Research Questions, primarily addressed in Chapters 3 and 4.

Both chapters focus on the attainment of the identified farmer goals, i.e., economic motivations, preferred pathways, and attitudes and values (**section 6.2**, **Table 6.2**). To compare the pathways towards these goals, a "successful" pathway was defined as one leading to the highest proportion of farmers attaining the same goal in the respective regional populations. In both chapters, different successful pathways were found. In Chapter 3, common conditions and pathways were found to lead to the prevalence of farmers wishing to (1) fulfill profit maximizing goals, (2) engage in modernizing or on-farm diversifying adaptations, and (3) sustain the valued cultural heritage associated with the olive plantations. These farmer goals are supported in a regional context where agricultural profits are sustainable and complemented by income subsidy schemes, and where social cooperative initiatives are present to promote cultural values and generational renewal, and further boost profitability. These conditions result in a regional sector where agriculture is revitalized, and a larger share of farmers (and farmland) remains active in the cultivation of olive plantations via more intensive, full-time farming. This confirms earlier findings, e.g., by Hernández et al. (2021) and Rivera et al. (2020), who demonstrate that regional cooperation across short value chains can foster sustainability of small farms. Collective action is however challenging to set up and maintain (Villamayor-Tomas et al., 2021) emphasizing the importance of social capital (Ptak et al., 2022). Conversely, prevailing "satisficing" agricultural income goals and off-farm income diversification prevail in the absence of social cooperative initiatives which provide opportunities to valorize local produce and stimulate a cultural drive and generational renewal. Higher olive oil prices or subsidies are in this case unable to retain as significant a share of farmers to full-time employment in agriculture, and the region is forecast to witnesses a shrinking agricultural sector and fewer investments in intensification in this latter scenario.

Contrasting pathways were also identified via the agent-based modelling investigation undertaken in Chapter 4. A first trajectory supports farmer goals tied to the modernization pathway and to adaptive behaviors. These goals prevail in a context of stronger climate impacts and ongoing policy mechanisms which largely do not place constraints on irrigation withdrawals. The modernization pathway promotes farm scale enlargement, resulting in a regional sector characterized by fewer, consolidated, farms undertaking frequent crop transitions and investments in irrigation to attenuate drought damages and increase agricultural revenues. In the second trajectory, widespread willingness to adapt alongside water policy constraints on irrigation withdrawals result in the prevalence of farmers opting for diversification adaptations instead of the modernization pathway (which is constrained, for example, by regulations on the cultivation of water demanding crops). Farmers are in this case less able to mitigate drought impacts and boost agricultural revenues. In the third pathway, the implementation of policy ensuring increased irrigation water supply, alongside low farmer willingness to adapt in the region (e.g., due to fewer climatic impacts), primarily see low adaptation levels and largest declines to farmland area while retaining the highest number of farmers to the sector. While this policy ensures irrigation supply and can therefore successfully buffer fields from drought impacts, the low inclination of farmers to invest in other adaptations results in overall strong declines to regional agricultural revenues.

These two modelling studies reveal how policy may lead farmers to pursue goals which may ultimately undermine the policies' very objectives. Chapter 3 illustrates the limits of income subsidy schemes in promoting product valorization, higher-intensity productions, and cultural farming motives – resulting in low generational renewal and more widespread agricultural abandonment, thus potentially falling short of broader agricultural policy objectives aiming for rural vitality. Chapter 4 illustrates how the implementation of two contrasting water policy mechanisms addressing (sustainable) irrigation in agriculture ultimately result in lower regional agricultural revenues, and thus do not contribute to economically sustaining the sector.

Table 6.2 – Pathways and conditions to the attainment of the characterized farmer goals and their respective implications as identified throughout Chapters 3 (Lesvos case study) and 4 (Romagna case study).

Enabling conditions and pathways	Attained farmer goals	Implications
East Lesvos case study (Greece), Chapter 3		
• Higher olive oil prices • Subsidies • Presence of social cooperative initiatives promoting valorization of local produce	• Modernization and on-farm diversification pathways toward profit maximizing goals • Fostered heritage values	• Large share of farmers remains active in agriculture (through generational renewal) • Low prevalence of land abandonment and de-intensification

• Absence of initiatives promoting on-farm diversification via the valorization of local produce	• Reliance on off-farm income diversification (as opportunities for on-farm income diversification are restricted) • Agricultural profit satisficing goals prevail • Gradual erosion of heritage values	• Large share of farmers quit the sector (low generational renewal) • High prevalence of land abandonment • High prevalence of low intensity farming
Romagna case study (Italy), Chapter 4		
• Large, experienced drought impacts and/or attitude shifts toward high willingness to adapt • No policies restricting water use consumption and ensuring water supply	• High drought risk perception • High willingness to adapt (high climate change awareness and openness to change) • Prevalence of all adaptation pathways, especially modernization	• Farm scale enlargement (fewest farmers, largest share of land under cultivation) • Highest irrigation withdrawal • Highest prevalence of water demanding crops • Fewest drought damages • Highest revenues
• Large, experienced drought impacts • Policies restricting water use consumption	• High drought risk perception • High willingness to adapt (high climate change awareness) • On- and off-farm income diversification pathways preferred over modernization	• Farm scale enlargement (few farmers cultivating large share of land) • Fewer uptake of water demanding crops • Lower irrigation withdrawals • More extensive drought damage • Strongest decline in revenues
• Few, experienced drought impacts and/or attitude shifts toward low willingness to adapt	• Low drought risk perception • Low willingness to adapt (low climate change awareness and openness to change) • Off-farm diversification	• Continuation of smallholder farming (largest share of farmers remain active yet cultivate fewest land) • Fewest drought impacts

• Policies ensuring increased irrigation water availability	preferred over on-farm diversification	• Strong decline of revenues

6.5. Mapping and modelling adaptation in Mediterranean agricultural landscapes

6.5.1. Insights for policy

The identified dimensions of farmer willingness and ability (**section 6.2**) and their role in determining the outcomes of policy mechanisms (**section 6.4**) are of value to ongoing debates regarding agricultural policy reform, particularly in the European Union. While the European Union's Common Agricultural Policy holds a broad range of incentive and regulatory mechanisms promoting rural development alongside agricultural income support, it has long been criticized for primarily favoring practices yielding higher economic returns over the delivery of public goods (Brown et al., 2021), resulting in the prominence of the modernization pathway at a cost for rural resilience. This thesis deepened our understanding of the mechanisms through which agricultural policy can and cannot support rural development. Chapter 3, for example, showed how area-based payments cannot sufficiently support smallholder farmers, nor capitalize on the existing potentials of local "landscape products" associated with more diverse societal benefits (García-Martín et al., 2021). In a context where these subsidies meet low agricultural profitability, a lack of collective action, and few alternative full-time employment opportunities, our results demonstrated that pluri-active and part-time farmers are likely to remain prevalent and partly bound to the sector either via a lack of employment alternatives or a desire to maintain valued family heritage (**Table 6.2**). The significance of the off-farm income diversification pathway has been recognized by other studies based in the Mediterranean region, where it is seen as a viable adaptation capable of supporting smallholder farmers in the maintenance of the traditional agricultural landscape (Giourga et al., 2008; Pinto-Correia & Vos, 2004).

Our modelling results from Chapter 3 however revealed that the prevalence of the off-farm income diversification pathway does not result in landscape stability and is symptomatic of progressing abandonment trends. This is, on the one hand, due to a vast majority of farmers being close to or past the retirement age and having low probabilities of successorship, as new generations in this context see little incentive to join the sector. On the other, it is primarily associated with a lack of sectoral profitability and investment capital. Under such conditions, farmers are pushed to seek alternative employment opportunities and engage in land de-intensification and abandonment, initiating an on-going path-dependent trajectory (Ch. 2). The 2005-2016 period has indeed seen a decline in the share of farms engaged in off-farm income diversification in Europe, as no policies are currently in place to support engagement in this pathway without it ultimately leading to farm exit (Shahzad & Fischer, 2022). Importantly, this trend is strongest when concerning low-productivity, smallholder farms.

Similar dynamics are revealed in the Romagna case study presented in Chapter 4. The region's current water policy environment has primarily centered efforts on securing water supply to farmers to maintain status-quo conditions. As adaptation and entrepreneurialism are not strongly incentivized, continued declines in regionally cultivated land are forecast (**Table 6.2**). These findings challenge the often-stated viability of the off-farm diversification adaptation pathway as a strategy for preserving traditional agricultural landscapes (and their associated benefits). Policies to support this pathway while ensuring continued partial engagement in agriculture could therefore act to increase the attractiveness of sustained agricultural activities. Interview results from Lesvos (Ch. 2) revealed that disengaged part-time farmers forecasting further disinvestments are also less likely to have relied on extension services, which could instead be rendered more accessible to stimulate productivity gains. More substantial results are perhaps likely to be achieved through greater direct income support to part-time and pluri-active farmers. This could come in the form of targeted agricultural subsidies which have instead partly excluded farmers whose agricultural time commitments and revenues only comprise a minority of their totals (Giourga et al., 2008). They may additionally comprise facilitated remittance structures and secured pension schemes to further contribute to household income stabilization in many Mediterranean regions where these mechanisms are currently lacking (Marzin et al., 2017).

Additional policy goals are also likely to support this adaptation pathway by fostering a cultural drive among farmers, as our interview results and further studies from the region (Giourga et al., 2008) identified feelings of stewardship as a primary motivation to maintain engagement in farming, even as a low-productivity and part-time commitment. A strategy toward the promotion of this value is tied to support for the expansion of local "landscape products", i.e., (quality) food products originating from distinct landscapes and representative of local farming heritage (García-Martín et al., 2021). Policy could choose to deliberately support the delivery of landscape products by facilitating local or international high-quality value chains (e.g., via Geographical Indication certification mechanisms). Such initiatives are likely to both favor the off-farm diversification pathway by fostering cultural farming values, as well as to directly boost the on-farm diversification pathway by allowing farmers to increase the value of their agricultural produce and/or broaden on-farm activities to include gastronomic and other agri-tourism services (García-Martín et al., 2021; Rivaroli et al., 2017). While not universally applicable, these findings hold relevance beyond the case study sites and across the wider Mediterranean Basin due to the widespread prevalence of landscape-specific farming systems in the region (e.g., olive landscapes or *montado* systems) delivering high-quality traditional produce sustained by high levels of landscape stewardship among the farmer population (García-Martín et al., 2021).

Our investigation in Romagna, explored in Chapter 4, showed how existing policy mechanisms under the European Union's Common Agricultural Policy are indeed stimulating diversification pathways by subsidizing shortened supply chains and product differentiation (e.g., on-farm processing facilities, organic farming), and agri-tourism infrastructure. These subsidies however present strict regulatory frameworks and administrative costs which may be too high to bear for some farmers. In these cases, and in cases where farmers strongly valued autonomy, parallel initiatives were set-up by farmers whereby similar benefits, e.g., in the form of price premiums, could be attained. In Lesvos, collective action by farmers in the form of social cooperatives similarly emerged to claim the underutilized potentials associated with the promotion of local landscape products. Agricultural policy may therefore alternatively work to provide a more favorable institutional environment for collective organization by farmers, e.g., via the provision of targeted funding (García-Martín et al., 2016).

In Romagna, the on-farm income diversification pathway was promoted under policies which favor dynamism and farm investments yet simultaneously constrain the modernization pathway. This was identified within a scenario exploring water policy restricting intensive water use and promoting norm engagement toward adaptation. This scenario saw strong declines to agricultural revenues and water consumption (by reducing investments in high-revenue and water intensive crops), yet a considerable share of land remained under cultivation, as farmers diversified their farms and were able to grow viable enterprises. In Chapter 3, engagement in on-farm income diversification was instead favored under conditions which simultaneously promoted modernization, as both trajectories ultimately involve a transition toward greater professionalism and intensification. Further work may therefore focus on identifying the broader environmental and social repercussions of each pathway, as to inform policy on respective trade-offs. Chapter 4 confirmed that greater sustainability with regards to water consumption lies outside of a strictly prominent modernization pathway, and relies on water policy shifting its focus toward restricting consumption, echoing calls throughout the broader region (Sowers et al., 2011). While environmentally sustainable outcomes were not explicitly investigated in Chapter 3, greater benefits are likely to be identified in a scenario where local produce valorization prevails, due to the lower negative externalities tied to its associated production practices. Recently published research has indeed found positive correlations throughout the European Union between landscape products under Protected Denomination of Origin, and areas of greater environmental value (e.g., presence of high nature value farmland) (Flinzberger et al., 2022).

Importantly, the Mediterranean-wide analysis conducted in Chapter 5 revealed that actions consistent with the modernization pathway (i.e., directly aiming to maintain or increase agricultural productivity) have lower applicability within areas most affected by climate change. In some cases, they see very little to no potential for implementation, for example in regions with insufficient capacity for irrigation supply. These regionalized production limits stress the importance of considering climate change impacts and adaptive capacities when targeting policy support, and furthermore identify where a move away from productivism and toward non-agricultural diversification may be needed. Within areas where adaptation is on the other hand currently limited, but deemed possible, the analysis in Chapter 5 identified land ownership, market accessibility, and poverty to be driving low adaptation capacities, revealing the importance of integrating agricultural support measures within broader mechanisms of rural development.

Altogether, incentives and voluntary schemes have been found to be disproportionately centered on promoting productivist measures with highest revenue potentials (Brown et al., 2021; Fayet et al., 2022; Scown et al., 2020). Embedding policy design and implementation within a process of local participation and experimentation can better reveal different dimensions of farmer willingness and ability and thus enable the design of more diverse mechanisms, such as current proposals to move from area-based income support to needs- or results-based payments (Herzon et al., 2018) which inherently place greater recognition on diverse farming realities. This requires greater efforts towards understanding relations between policy drivers and farmer behavioral transformations tied to the reformulation of goals.

6.5.2. Research outlook

This thesis implemented three core methodological insights suited to the properties of complex social-ecological systems (**section 1.3.2**). The first insight concerned the need for contextualized analyses and led to the empirical investigation of multiple case studies within the Mediterranean region. While these case studies were selected to reflect diverse adaptation pathways, they do not suffice to illustrate the range of different (crop-based) farming systems which characterize the Mediterranean. In particular, the identified farming types in Chapters 2-4 did not include farmers akin to the "survivalist" and "professional intensifier" types belonging to the global land use decision-making typology developed by Malek et al. (2019). These two types are respectively represented by farmers which globally hold among the lowest and highest financial means, land tenure security, and power status. Despite holding more widespread importance in other world regions, both types are relevant to the Mediterranean Basin, with the survivalist type holding relatively greater significance in Turkey and across northern Africa (Malek & Verburg, 2020). Past studies have revealed the importance of these two types for understanding specific landscape change processes. While the survivalist farmer is associated with low compliance with regulatory measures (associated, for example, with deforestation), the professional intensifier is associated with extreme forms of expansion and intensification and low implementation of environmentally-friendly farming methods (Malek et al., 2019).

There is a need to further investigate the characterization of survivalist and other smallholder farmers across the Mediterranean, both within Europe (Bartkowski et al., 2022) and even more so in southern countries where investigations have thus far been considerably more scant (Malek & Verburg, 2020; Marzin et al., 2017). In particular, characterizations in the southern Mediterranean have largely failed to document processes of land fragmentation and off-farm diversification, meaning agricultural policy cannot be tailored to the specific needs of some smallholder farmers (Marzin et al., 2017). The investigation of professional intensifiers and agri-businesses in the Mediterranean is an equally important focal point for future research, as these actors are gaining prominence and are increasingly recognizing and capitalizing on their power to determine landscape-level sustainability (Salvini et al., 2018). This exploration will importantly require expanding the analysis of actors beyond agricultural producers, as was done in this thesis, to other influential actors comprising agricultural value chains.

While the case studies addressed by this thesis in part relied on interview data, this process remained strongly informed, complemented, and reliant on secondary sources and behavioral theory (**section 6.3**). Partly grounding our work within existing regional data (e.g., agricultural census information) increased the potential for comparability and generalizability of our results, yet also failed to challenge some of the shortcomings of these resources, particularly by not seeking to deliberately differentiate farm-level dynamics based on often overlooked (and undocumented) determinants of social structures, e.g., gender roles. The stakeholder workshop conducted as part of the research presented in Chapter 3 represented an effort to identify additional influential drivers and farmer attributes and confront assumptions, and indeed resulted in stakeholders interrogating the role of gender in local land use decision-making (Villamor et al., 2014). As part of an enhanced characterization and exploration of more diverse farming systems, future research may therefore explicitly scope determinants of social organization and power relations and investigate their role in relation to regional landscape change.

The second methodological insight implemented in this thesis addressed the potential of agent-based modelling to simulate multi-scalar feedbacks and adaptation processes characterizing complex social-ecological systems. This work was undertaken in Chapters 3 and 4, and focused on advancing the modelling of influential farmer goals by capturing (1) a greater range of objectives, including farm income diversification and climate adaptation (Holman et al., 2018; Huber et al., 2018), and (2) the possibility for farmers to change their objectives over time in response to changing socio-economic and environmental conditions (Le et al., 2012). As discussed in the respective chapters, however, further important progress may still be made in both aspects. With regards to the modelling of a broad range of preferred adaptations, there remains a need to unravel dynamics tied to income diversification trajectories more closely, notably by investigating the specificities of different actions (e.g., adoption of organic agriculture vs. integrated management), and by integrating feedbacks with the labor market and availability of on- and off-farm employment. For climate-related adaptations, agent-based modelling is increasingly being applied within the field of socio-hydrology to simulate needs and efficacy of adaptations at the farm and landscape scales (Wens et al., 2019). Yet, additional research is needed to capture feedbacks from multiple climatic hazards, as communities across the Mediterranean Basin will likely face a diversity of (consecutive) stressors (Cramer et al., 2018).

The agent-based models presented in this thesis simulated the consequences of shifting farmer goals that were identified in the interviews, yet the processes leading to these shifts remained primarily grounded in theory. One example found in Chapter 4 relates to simulated increases to farmer drought risk perceptions and propensity to adapt following experienced climatic impacts (following Grothmann and Patt (2005)). Empirical evidence on this process however reveals a more complex picture, as exposure to adverse climatic impacts within different farming communities has been found to result in both higher risk aversion and higher risk tolerance (Finger et al., 2022). This reflection is in agreement with calls for greater consultation between simulation modelers and behavioral scholars investigating the empirical validity of theoretical concepts (Muelder & Filatova, 2018).

A related focal point for future research refers to the potential of agent-based models to further integrate feedbacks between farmer goals and action by formal and informal institutions. The stakeholder workshop presented in Chapter 3 referred to this knowledge gap in relation to the emergence of collective action, stating this process may be facilitated by policy but also conversely rise to contrast its inaction. Unravelling these dynamics is crucial for identifying and exploring how transitions to agricultural sustainability may occur (Gaitán-Cremaschi et al., 2019). It will however require agent-based models to begin simulating institutions as responsive, rather than exogenous, forces to social-ecological systems, and will by extension necessitate the inclusion of further actors beyond the farm (i.e., shift from modelling agricultural systems to modelling food systems). Despite the challenges of unravelling and simulating such dynamics, agent-based models are relatively better suited to accommodate for this transition than other models, and may draw on participatory insights from stakeholder network analysis (Hauck et al., 2016).

The final research chapters of this thesis, Chapters 4 and 5, explicitly touch upon the need for research to explore "transformational" adaptation in a context of climatic change. In Chapter 4, this was investigated by farmers re-evaluating their goals and implementing adaptations which involved substantial changes to their farming systems, borrowing from definitions of transformational change by Rickards & Howden (2012) and Vermeulen et al. (2018). This perspective was similarly incorporated in Chapter 5, which defined the explored transformational adaptations as actions involving change beyond the introduction of a single practice and more likely to be effective in areas of greater climatic impact, following the approach set out by Rippke et al. (2016). These perspectives on transformation are important as they place emphasis on agency and decision-making alongside capturing the nature of enacted changes, inviting reflections on their respective transaction costs and potentials to meet unprecedented challenges. Yet, under other definitions, these examples may be found to represent quite a narrow view of transformation, for example by disregarding "novelty" aspects (Kates et al., 2012), and by not taking a (social-ecological) system-wide perspective where the focus lies on addressing the root causes of vulnerability (Deubelli & Mechler, 2021).

These alternative definitions shift the analytical emphasis from transformational *outcomes* (explored in this thesis) to transformative *processes* (Vermeulen et al., 2018). The investigation of such processes via means of agent-based modelling will require a more integrated simulation of socio-cultural and institutional change (as discussed above). In turn, this will also demand a different approach to scenario design than the one implemented in this thesis. This brings us to our final methodological reflection in the context of complexity, climate change, and social-ecological systems research. Chapters 3-5 of this thesis made use of scenarios which, despite abstract names (e.g., "Bright vs. Doom", Ch. 3), represented explorations pertinent to presently occurring farming discourses and largely addressing the extension or contraction of existing policy instruments. While such approaches are necessary to scope the potential and limits of present action, further work is urgently needed to combine science and imagination and boldly envisage transformative trajectories toward sustainable and just futures. This approach will require greater engagement with normative questions exploring not just what "could" happen, but also what "should" (Nalau & Cobb, 2022).

Supplementary Information

A. Chapter 2

A selection of key Supplementary Information is hereby provided. For a comprehensive overview of this chapter's Supplementary Information, please refer to the online version of the published article this chapter is based on, available at the following link:
https://doi.org/10.1007/s10113-017-1276-4

- **Landscape photos ranked by tourists during the preference survey**

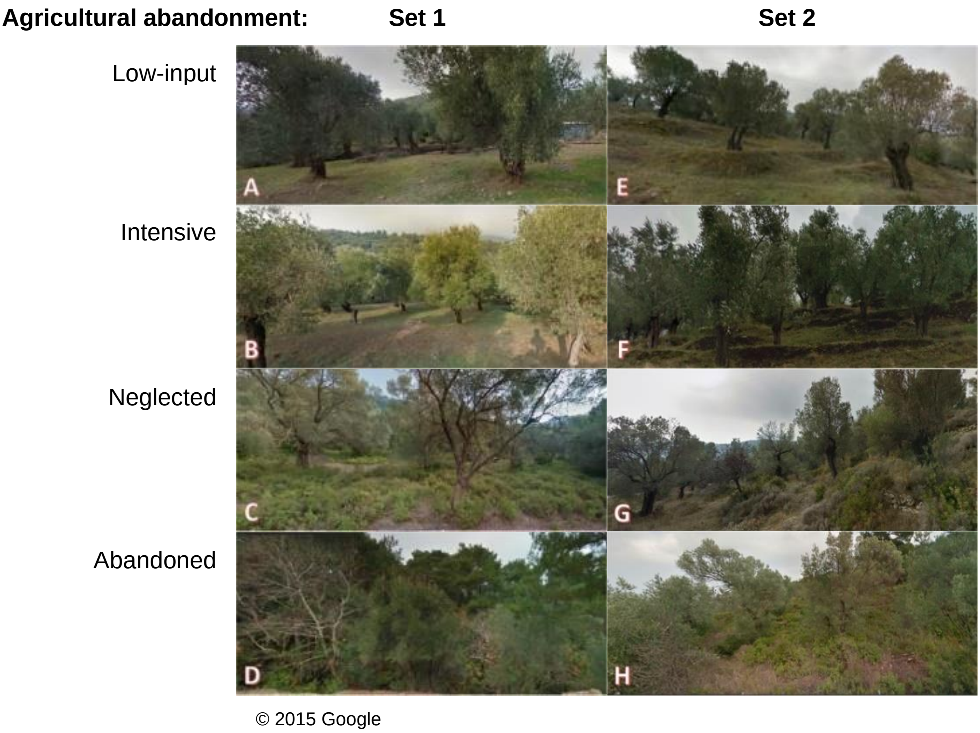

Figure A1 – Landscapes ranked by tourists during the preference survey in respective sets illustrating processes of agricultural abandonment and housing sprawl (urbanization). Sets 1 and 2 utilize Google Street View (2015) panoramic imagery.

B. Chapter 3

A selection of key Supplementary Information is hereby provided. For a comprehensive overview of this chapter's Supplementary Information, please refer to the online version of the published article this chapter is based on, available at the following link:
https://doi.org/10.1016/j.landusepol.2017.03.022

- **ABM description following Overview, Design Concepts and Details (ODD + D) template**

Table B1 - Model description follows the template set out by the ODD + D protocol presented by Müller et al. (2013), expanding and modifying the original ODD protocol (Grimm et al., 2006, 2010) to more closely elaborate on the human decision-making components in ABMs.

Outline (→template)		ODD + D Model description
Overview	Purpose	The purpose of this study is to explore how Integrated Landscape Initiatives (ILIs) and macro-level drivers alter agent behavior and consequentially affect landscape change, unravelling complex human-environment dynamics at play within cultural landscapes prone to agricultural abandonment. This work was undertaken in contribution to the EU's FP7 HERCULES project. By informing an ABM empirically and utilizing an iterative model development approach in collaboration with experts in cultural landscape change and local farming community members, the study aims to promote societal discussions in cultural landscapes witnessing ongoing abandonment trends within the case study area and beyond. As such, the model is designed primarily for the scientific, policy and farming communities interested in similar dynamics. The ABM specifically aims to: (1) Model and evaluate the extent to which underlying drivers affect landscape changes in the region of Gera under a "Bright" and "Doom" scenario set to respectively disfavor and favor the continuation of abandonment processes by affecting the profitability of the agricultural sector (2) Model and evaluate the extent to which the implementation of ILIs mitigates or enhances changes under each scenario influencing behavioral attributes of agents alone (3) Enhance representations of behavioral transformations, specifically towards new generation farmers (4) Promote societal discussion on landscape dynamics (and their representation) between

		and amongst local stakeholders and landscape experts.
	Entities, state variables and scales	The model is based on attributes belonging to one of five separate entities: individual farmers, patches (pixel-level units comprising fields), fields, farms (collection of fields belonging to the same farmer) and a global environment determining external influential processes, i.e. the state of the macro drivers. Both fields and farmers are coded as "agents". Exogenous factors acting as drivers of change in the model explicitly relate to the macro-level drivers of olive oil prices, labor wages and agricultural subsidies. ILIs were not modelled as separate collective entities but operated if "activated" in a model run by altering behavioral attributes of adherent farmers. The model is spatially explicit and geo-referenced to cover the former municipality of Gera, Lesvos (87km^2). It makes use of spatial datasets related to land-cover, slope, cadastral boundaries, accessibility to road network, road network, land suitability and location of towns. All landscape changes occur within the olive grove land-cover class only as delineated within the 2012 land cover dataset. The baseline year was set to 2012 according to the most recent land cover dataset available. The model runs at annual intervals for a total of 25 years (time-steps).
	Process overview and scheduling	The model begins with a computation of the total farmer population; every year 1% of the total farmer population is added as new arrivals. As data specific to "newcomer" farmers is not available, their farmer type is set to match the predominant type in the municipality that given year. This typology assignment simulates a positive feedback between multi-level drivers favoring a certain farmer type and attributes characterizing the farmer population as identified in the farmer survey, e.g. a period of low profitability and low adherence to ILIs is associated with prevailing detachment. All farmers age one year and some leave the system as they reach their individual life expectancy, set according to country statistics. If a successor is present it will inherit land and the majority of parent characteristics, if no successor is present all land is abandoned. A successor's cultural drive (defined by a desire to maintain land under family ownership and a refusal to sell) is not directly inherited but re-established under probabilities for their inherited farmer type, allowing for the possibility that the parent farmer has switched farmer-type and may therefore pass on different motivational goals to its successor. Similarly, (if ILIs are implemented in the model run) a successor farmer will re-consider joining ILIs and will not necessarily join despite the parent farmer's membership. Both new arriving farmers and successors are considered "new generation" farmers.

	Every year all farmers calculate their farm yield (based on slope and management intensity), profits and costs to determine their annual wealth and assess how this compares to the previous years'. Accessibility of a farmer's fields influences the farmer's transport costs. Macro drivers of olive oil prices, subsidies and labor wages are updated based on annual rates of change and hereby affect a farmer's annual wealth computation. Following an assessment of new total land area and wealth, farmers decide whether to consider expanding their system or whether they are better off scaling-down or continuing under present conditions. The probability of an action taking place is set according to a farmer's goals (cultural or non-cultural), their level of schooling, past actions, whether their profits have been increasing or declining, their age and imitation strategy. While cultural farmers choosing to shrink their system will consider abandoning rather than selling, the opposite is true for non-cultural farmers seeking profit maximization. A single plot is assigned to a decision regarding the purchase or selling/abandonment of land; the plot is selected according to whether it has the highest or lowest land suitability value respectively. Following a period of abandonment of 5 years, fields witness a land-cover transition to wooded grassland and shrub, after an additional period of abandonment of 15 years the fields are considered forested. As land undergoes land-cover changes (to shrub or forest) the land suitability value of land decreases, in turn decreasing the likelihood of abandoned fields being purchased if more suitable plots are available for sale within the market. If a farmer buys a plot that was previously abandoned, the farmer undergoes a one-off land conversion cost and the plot undergoes an increase in land suitability value. Type-switches may occur in two instances. Following actions undertaken in the given year and depending on a farmer's cultural drive, age, declining or increasing profits and farm area size, a farmer may undergo a type-switch. These may result in changes to a farmer's management intensity and hired labor units, leading to de-intensification or intensification of a farmer's land. Direct type-switches between disengaged farmers and professional farmers are not considered. In a second instance, if a farmer reaches retirement age of 65 and does not have a willing successor, they will continue farming under the present type unless they are of the professional type, in which case they will switch to the active part-timer type and de-intensify their system. If ILIs are activated in the model run, each farmer that is not already a member will consider joining. Their diffusion is enhanced by imitating farmers responding to

		an increasing portion of farmers in the region having already adhered to the initiatives, the inquiring farmer's cultural drive, their education level and use of external consultations. Joining an ILI in turn increases a farmer's management intensity to the highest level, changes (or, if already cultural, maintains) a farmer's motivational goals from non-cultural to cultural, introduces the farmer to external consultancies and increases the probability that the farmer will have a willing successor. The increase in management intensity was established due to survey results identifying higher intensity levels amongst farmers adhering to social cooperatives and the nature of activities promoted by these initiatives (integrated pest management, organic certification, provision of extension services), focusing on increased frequency of management activities (e.g. pruning) as much as on the adoption of novel inputs or practices.
Design concepts	Theoretical and empirical background	General concepts underlying model design reside within behavioral theories as well as broad agronomic and economic processes. Influential macro drivers relevant for sectorial profitability and farmer's annual wealth computation were derived from de Graaff et al. (2009). Limited availability of spatial datasets related to biophysical conditions of relevance to agronomic yields resulted in the more ad-hoc approach adopted for yield computation, reliant solely upon slope of fields, frequency and intensity of the farmer's management practices and inputs and hired labor units. Returns to labor are assumed as management intensity and hired labor are weighted differently within revenue and cost computations. Lack of spatial information regarding land ownership furthermore resulted in the constructed hypothetical cadastral dataset, informed by land-use GIS data from 2012, local census data from 2011 (ELSTAT, 2011) and spatial trends identified in in-depth interviews with 100 farmers of the municipality. Assumptions behind farmer decision-making are based on a combination of established theory, ad-hoc rules and empirical observations. Farmers are boundedly rational and influenced by cultural and economic goals as revealed via farmer interviews and confirmed in a local stakeholder workshop. Empirical evidence from the interviews and workshop furthermore revealed age to be an influential factor in land-based decision-making. Farmers are assumed to favor the repetition of past actions in their farm management decision-making and to favor transition to alternative non-agricultural employment if they have attained a higher level of schooling, processes elaborated or similarly adopted in Valbuena et al. (2010) and Acosta et al. (2014) respectively. All farmers are assumed to receive agricultural subsidies in equal amounts, thus perceiving

		changes equally. Spread of ILI membership takes place according to the Theory of Planned Behavior, utilizing a similar approach to that modelled by Kaufmann et al. (2009); relative contribution (weights) of the different components were assumed to be equal. The assumed ability of ILIs to alter agent behavior and promote passing of land to successors draws on respective findings of García-Martín et al. (2016) and Sottomayor et al. (2011). Input data related to farmer and field attributes was largely aggregated at the farmer-type level. The application of these design concepts within the model is elaborated within the manuscript in **sections 3.2.4** and **3.2.5**.
	Individual decision-making	Decision-making takes places at the individual (farmer) level and specifically relates to farm expansion or shrinking (affecting one plot per annual time-step), farm intensification or de-intensification (affecting the farm system as a whole), decisions to join ILIs and decisions to undertake a type-switch. These decisions are not independent of each-other, as altered farmer behavior from ILI membership or farmer type transitions influence the way farmers choose the management and scale of their farm, and vice versa. No optimization or utility maximization approaches are adopted within decision-making. Rationality lies within all farmers wishing to make a profit from farming by purchasing the most productive plots and selling or abandoning the least. While non-cultural farmers sell their plots as part of their profit-making goals, cultural farmers are more reluctant to scale down and only do so by abandoning their plots, thus not pursuing profit-making in this decision-making aspect. Cultural farmers furthermore wish to see a revitalization of their sector and agricultural heritage, and in consequence are more likely to adhere to ILIs and intensify their systems by increasing their knowledge base. Decision-making is ultimately dependent on a farmer's agricultural knowledge assumed within a farmer's past experiences and interactions, and thus on a farmer's willingness to assimilate knowledge from external sources. Decisions to expand or shrink the farming system and adhere to ILIs are dependent on the occurrence of a series of farmer agent attributes, alongside the farmer's accrued wealth and total farmland area. The more relevant attributes are "present" for farmers, the more likely they are to undertake the action. The decision maintains a probabilistic element as randomly generated numbers are evaluated against the farmer's likelihood of action probabilities. Agents adapt their decision-making behavior as a result of changing exogenous and endogenous drivers. Macro drivers directly affect a farmer's annual wealth

		computation by increasing or decreasing agricultural subsidies, labor wages and olive oil prices. These changes influence a farmer's ability to purchase new land and affect likelihood of scaling down system. Consequentially, exogenous factors may affect type-switches indirectly by altering a farmer's total farmland area and from the assessment of present profits in respect to the profits made in the previous year. ILI membership furthermore alters agent behavior, directly for member farmers by promoting higher intensity farm management, cultural goals and interactions for knowledge transfer. Indirectly, growing ILI membership promotes transitions towards professionalism and positively feedbacks to more farmers adhering, primarily through imitating and consulting farmers. Spatial aspects play a role in decision-making in the computation of annual yields (based on slope), in the selection of plots for buying or selling transactions (dependent on the land suitability layer) and in the distribution of plot ownership (cadastral layer) dependent on survey-derived probabilities of occurrence of farmer type plot ownership across the land suitability layer. Temporal aspects play a role in decision-making by accrued wealth and farmland area; thresholds related to each of these attributes affect decision-making regarding purchase of plots and type-switches. Farmer agents do not explicitly consider uncertainty or risk in their decision-making.
	Learning	Learning is dependent on interactions of farmers (via imitation and external consultations) and past experiences. Farmers are more likely to pursue a certain action if they have already undertaken it in the past, modeling internal memory. It is also implied as part of the behavioral changes that occur from adhesion to ILIs manifested in changes to management intensity and behavioral attributes, potentially driving a farmer towards cultural goals. Collective learning is not considered.
	Individual sensing	Farmers sense changes to olive oil prices, subsidies and labor wages. They are aware of land suitability values of plots on sale (which represent their financial value) and of the predominant farmer-type in the region. As farmers join ILIs they start making use of external consultancies. A farmer is not aware of the state variables of any other farmer in the municipality. Costs of joining ILIs or of gathering information by means of consultancies are not directly considered in the model. However, by increasing management intensity as a result of membership and consultations, farmers will witness a change in their yearly revenue as higher costs are assumed from new

		inputs as well as improved yields. The sensing process is not considered to be potentially erroneous.
	Individual prediction	Farmers do not aim to predict future conditions; they base their yearly decision-making on their current situation, past actions and comparison of present and past profits.
	Interaction	Farmers directly interact between themselves via imitating and consulting farmers, responding to the predominant farmer type within the region and the number of farmers joining ILIs. If the majority of farmers in the region are of the professional type, imitating farmers are more likely to expand their farming systems. If either of the remaining two farmer types presents the predominant type in the area, imitating farmers are more likely to disfavor system expansion. Imitation is set to the predominant farmer type as opposed to proximity-based neighbor imitation as farmers in the region largely own several plots scattered across the case study area. ILIs, if activated, are by definition seen as imposed and not emergent. They change behavioral properties of adherent farmers, maximizing their management intensity, instating a cultural drive, increasing likelihood of having a willing successor and introducing the farmer to external consultancies. Imitating and consulting farmers are more likely to adhere to ILIs. Indirect interactions occur as a result of buying and selling or abandonment of land; as these decisions occur within a finite space they reduce the possibilities of other farmers undertaking similar decisions. Furthermore, values related to land suitability are normalized, thus plot selection is dependent on the plots placed on sale by all farmers.
	Collectives	Collectives represent the social networks present within the model. While ILIs are not represented as separate agents, their effect as a collective is modelled by altered farmer behavior of adherent farmers. Their diffusion is determined by a non-member farmer's attitude, subjective norms and perceived behavioral control, as modelled by Kaufmann et al. (2009), utilizing Theory of Planned Behavior to explore diffusion of organic farming practices by means of an ABM. A farmer's attitude was equated to the farmer being culturally vs. non culturally driven, subjective norms are set according to a farmer being an imitator and the share of the farming population which has adhered to ILIs while perceived behavioral control is a function of a farmer's education level and use of external consultations.
	Heterogeneity	The farming community is considered heterogeneous as farmers have differing values for their attributes. While farmers belonging to the same type are more likely to share similarities in attributes, these remain set according to type-specific probabilities of occurrence,

		thus maintaining some within type heterogeneity also. Maximum manageable farm size is the same for all farmers, representing the value past which farmers will no longer choose to expand their system despite sufficient wealth. Once retired, this value declines yearly and equally for all farmers. The model includes type-specific area constraints, notably the maximum manageable farm size for active part-timers and the minimum manageable farm size for professional farmers, both of which implement equal values for all type members. The third sub-module (decide and implement actions) runs the same functions for all farmers in the calculation of their yearly revenue and subsequent decision-making. While cultural farmers that opt for scaling-down of system will choose to abandon, non-cultural farmers will opt to sell. Because model functions are run individually for all farmers and are based on the occurrence of a set of field or farmer attributes, they result in heterogeneous values across the farming community.
	Stochasticity	Several processes within the model contain stochastic elements. Agent attributes which are randomly set are the past profits of starting farmers (stable increasing or decreasing), the number of labor units (between 1 and 6) set if the farmer is hiring labor and the age of newcomer or successor farmers, set randomly between a minimum of 18 and maximum of 38 years of age. The initial abandonment extent is set to 32% of fields (based on historical decline in yield productivity in maximum years) selected randomly from the cadastral layer, while plots purchased by newcomer farmers at every time-step are also selected randomly. The model's probabilities were informed empirically or following model calibration and sensitivity analysis, the latter referring to probability values for undertaking a land-based action, undergoing a type-switch, joining ILIs or having a willing successor following ILI membership. These values maintain a partially stochastic element. As the interview data determines the probability of an agent of a certain farmer type having certain attributes or attribute values, the model runs random draws based on these probabilities.
	Observation	Key outputs considered are related to the magnitude and spatial extent of agricultural abandonment and re-wilding taking place under the different scenario storylines, as well as changes to total farming population and typology composition, assessed with and without the implementation of ILIs. Additionally, landscape changes related to intensification and de-intensification of cultivated systems are assessed under the different scenario conditions, and an understanding of generational changes in farmer behavior quantified.

		These emerging outputs are recorded in the ABM interface at every time-step.
Details	Implementation details	The model was built in NetLogo version 5.3.1 making use of the GIS extension. Output spatial datasets and the ABM will be made publicly available upon acceptance of the paper (see www.environmentalgeography.nl).
	Initialization	At the time of initialization, 32% of fields are considered abandoned for more than 5 years and are thus displayed in the interface as wooded grassland and shrub areas within the olive plantations. This is the same in every model run, however the field selection process is stochastic and thus the abandoned landscape pattern differs in each model run. As farmers are stripped of ownership of their field once it becomes abandoned, the number of farmers at initiation also varies depending on the 32% abandoned field selection, as farmers who lose all their fields will quit the system altogether. In the start year, the predominant farmer type is always the detached farmer according to the farmer typology distribution identified within the interviewed sample. Each group of fields with the same Farmer ID generates its managerial farmer based on the imported cadastral map via the GIS extension; farmers are then parameterized and their attribute values set: past profits are randomly allocated as declining, stable or increasing, life expectancy is set and the GIS imported farmer type informs the probability of the remainder attributes occurring. All runs, irrespective of scenario and ILI activation, begin with 11% of the farmer population as ILI members (a value not influential in a model run whereby ILIs are not activated); the value was obtained by the portion of farmers identified as social cooperative members also within the interviewed sample. The underlying drivers begin at equal values within both scenario storylines.
	Input data	With the exception of imported GIS layers, the model does not use input data from external sources.
	Sub-models	See **Table B2**.

Table B2 – Descriptive outline of model commands following initialization (i.e. run at every time-step) listed in chronological order; illustrating the "sub-models - details" component of the ODD + D protocol presented by Müller et al. (2013), expanding and modifying the original ODD protocol (Grimm et al., 2006, 2010) to more closely elaborate on the human decision-making components in ABMs.

Sub-model cluster	Command	Task description
Update	Reset timer	Reset timer.
Demographics	Compute predominant farmer type	Computes the predominant farmer type across the region and displays type on interface.
	Update farmers	Increase age of all farmers by one year, re-set their age class and maximum manageable area size if retired.
	Death	Farmers that reach their individual life expectancy pass land on to successor if present (who inherits or re-sets attributes), if no successor is present fields are abandoned.
	Retirement	Farmers that reach 65 years of age pass land on to successor if present (who inherits or resets attributes), if no successor is present professional farmers will switch to the active part-timer type and de-intensify their farm system, while the remainder farmer types continue farming under increasing area constraints.
	Newcomers	The number of newcomers is set to 1% of the annual farmer population. Newcomer farmers are assigned the predominant farmer type and begin farming by acquiring one vacant field in the region. If the field had been placed on sale, the selling farmer gains profit from sale of field. If the field was previously abandoned, the value of the field will increase due to its conversion from wild to cultivated state.
Scenario-setting	Scenario settings	The starting values to the macro drivers altered by scenarios are set (these are equal under both Bright and Doom conditions). Annual rates of change for macro drivers under Bright and Doom conditions are also set, depending on which scenario is chosen in the interface.
	ILI implementation	Only runs if ILIs are activated in the interface for the simulation. If so, farmers which have decided to adhere to ILIs will undergo annual increase/maintenance of high management intensity, will adopt/maintain a cultural drive, will make use of external consultations and calculate a new (higher) probability of having a willing successor.

Deciding and implementing actions	Computation of drivers	The values of macro-drivers are adapted according to the annual rates of change.
	Computation of yield	Computed at the patch level based on the patch slope value. Yield is then summed across all fields belonging to a farmer; farm yield is then calculated in consideration of the farmer's management intensity and hired labor units.
	Computation of production costs	Calculated based on a farmer's management intensity and farm size.
	Computation of transport costs	Calculated based on the average accessibility of a farmer's fields; field values are then summed to provide a total cost value per farmer.
	Computation of wealth	Farmers calculate total costs, summing transport and production and conversion costs if plot was purchased in an abandoned state. Annual profits are calculated from the annual costs and yields and accounting for yearly oil prices, subsidies and labor wages. The annual profit is added to a farmer's accrued wealth.
	Normalize land value	The land value of fields is normalized between 0 – 1.
	Decide probability of action	Farmers calculate the annual minimum value of wealth required for purchases based on the most expensive plot on sale that given year. If farmers have enough wealth but have reached the maximum manageable land area they will decide to continue without shrinking or expanding their farm. If they have enough wealth for buying and have not reached the maximum manageable farm area, they will proceed to determining action by calculating their probability to buy or continue with no change [determine action function 1]. If farmers do not have the required minimum wealth for land purchase, they will proceed to calculating their probability to shrink farm or continue with no changes [determine action function 2].
	Determine action	Determine action function 1: these farmers calculate their probability to buy based on the occurrence of a set of attributes, notably: past expansion, imitation in a prevailing professional context, and not belonging to the retired age class. The probability is run against a random draw to determine whether the farmer buys or continues. Determine action function 2: these farmers calculate the probability to shrink their system; probability increases based on past profits not showing an increase, belonging to the young

		age class, having shrunk in the past, having attained a higher level of schooling and belonging to the younger age group. If farmers are culturally driven they opt for abandonment, if they are not culturally driven they opt for selling. The probability to shrink is run against a random draw to determine whether the farmer shrinks or continues.
	Assign plot to action	A buying farmer will be assigned the plot with the highest land (suitability) value that is currently either placed on sale or abandoned. If the field had been placed on sale, the selling farmer gains profit from sale of the field. If the field was previously abandoned, the value of the field may increase due to its conversion from wild to cultivated state and the buying farmer will incur a cost. Shrinking farmers will sell or abandon the plot with the lowest land (suitability) value. While farmers who place their plots on sale will continue management until they are sold, farmers who abandon "loose" ownership and may thus no longer perform any commands over their former plot. Farmers past buying or shrinking status is updated accordingly.
	Update sub-process	A farmer recalculates his total farm area following transactions. A farmer calculates whether new profits have been stable, increasing or decreasing compared to the previous years and updates attributes accordingly.
Establishing individual typologies	Type-switch	Farmers below retirement age hereby may undergo type-switches. Active part-timers having previously opted to continue without expansion or shrinking of system, if above 50 years of age, not culturally driven and having witnessed stable or declining profits will run a probability to switch to the detached farmer type. Alternatively, if their farm size is above the maximum manageable farm size for their category they will run a probability to switch to the professional type. Detached farmers who are culturally driven and have a farm size at least half of the maximum requirement for active part-timers will transition to the active part-timer type. Professional farmers whose farm size is below the minimum area threshold required for their farm type will transition to the active part-timer type. All type-switch changes are accompanied by farm intensification or de-intensification accordingly. Fields are updated

		to their new and respective owner farmer types.
Consider ILI membership	Consider ILI membership	Farmers that have not yet adhered to ILIs consider joining based on their level of schooling, use of external consultations, imitation strategy, proportion of farming population that has already adhered to initiatives, cultural drive. The probability is run against a random draw to determine whether the farmer joins or not.
Implement land-cover changes	Implement land-cover changes	Keeps track of length of abandonment period of fields. Implements land-cover changes resulting from intensification of fields, de-intensification of fields, short and long term abandonment, on both field and patch attributes. Land (suitability) values are updated following long or short term abandonment.
Update	Tick	Time advances by one year.
	Show timer	Time is shown.
	Update view	Imports, establishes and updates settings for how spatial layers are viewed in the interface – keeps track of visualizing changing land-cover and land ownership.

C. Chapter 4

A selection of key Supplementary Information is hereby provided. For a comprehensive overview of this chapter's Supplementary Information, please refer to the online version of the published article this chapter is based on, available at the following link:
https://doi.org/10.1016/j.agsy.2020.103024

- **Details on model characterization**
  - **Interview procedure**

We first contacted three public officers of the two local LRIC in June 2017 to define guiding interview questions, identify the occurrence of different farm production "hotspots" and establish contact points for subsequent interviews. The interviews with key informants were conducted in July 2017, addressing 5 officers and technicians of the two local LRIC, 2 officers from one of the main farmer ("service") cooperatives in Romagna, 2 directors of local farmer production cooperatives, 1 officer of the local Agrarian Consortium and 1 officer from the most prominent farmer union in Romagna. Each key informant also served as an entry point for the farmer interviews and helped arrange field meetings in the research municipalities. Interviews with key informants aimed to investigate (1) past drivers of change in Romagna's agricultural sector, (2) past adaptation investments targeting water scarcity, (3) expected future impacts of climate change on agriculture in Romagna, and (4) the role of the informant's organization in guiding past and future adaptation initiatives. Farmer interviews addressed (1) farm(er) characteristics and management, (2) past drought adaptations to the farm system and motivations for change, (3) knowledge sources and networks, (4) socio-cognitive determinants of drought adaptation (derived from Grothmann & Patt (2005)) and (5) likelihood of future implementation of (transformational) adaptations and respective barriers or enablers.

  - **Interview analysis**

Model characterization was partly based on the quantitative and qualitative analysis of interviews undertaken with farmers and key informants. We followed the qualitative content analysis methodology outlined in Flick (2014). The interviews were transcribed and the text initially partitioned based on its description of specific farm-based actions and other entities of the MoHuB framework (Schlüter et al., 2017) (section 3.2, manuscript). Where the transcribed text described a process (i.e. a link between two or more entities), we coded (1) whether this process represented a positive or negative trajectory (identifying drivers vs. barriers) and (2) details on the relevant model entities involved in the process (external vs. internal goals, values, attitudes or assets). We additionally transcribed and coded text which did not describe a process but rather provided a detailed description of one or more of the model entities.

For the identification of attitudes and values, we used definitions by Schwartz (2012), where values are "beliefs linked inextricably to affect" which "refer to desirable goals that motivate action" and "transcend specific actions and situations", and attitudes are "evaluations of objects as good or bad, desirable or undesirable" and are determined by underlying values. While attitudes were directly identifiable in the statements made by interviewees, values were inferred from (1) descriptions of motivations and general approaches to farm management and the implementation of specific actions (e.g. "Innovation", Farmer-38: "*You need knowledge prior to interest, not everyone has it or wants to have it, it requires a lot of work […] a lot has come out of my own initiative, I've often followed courses to stay on top of things*", and (2) from the stated attitudes themselves (e.g. "Conservation", Farmer-36: "*I'm worried about water in the CER, it's losing a lot. We need to increase water savings and change irrigation systems - no more slide irrigation*"). We used the Theory of Basic Values of Schwartz (2012) as a guiding framework to aid the clustering of identified values under four over-arching, and related, dimensions (**Table C1**). Values relating to "Ambition" were furthermore used for the formulation of goals, as they revealed distinctions between farmers aiming to maximize profits vs. others satisfied with lower incomes. Attitudes stated by interviewees (e.g. on fairness of water pricing) which did not explicitly reveal a relation to adaptation decision-making were excluded from the model.

Some external variables which were identified in the interviews (notably: pests, labor availability, other knowledge sources, non-drought climate events and water trading mechanisms) were also ultimately excluded from the model either due to data limitations or if outside our study's scope. Similarly, the model does not include adaptations relating to insurance approaches (as these are only related to non-drought climate hazard), changing farm legal status (not inducing direct changes to the farm structural variables included in the model), and adjusting harvesting periods and irrigation timing (due to inadequate temporal detail). Technical knowledge assets were also excluded from the modelled farmer characteristics, but instead were captured in a farmer's openness to change values, as statements revealed a relation between the two variables. Experiential knowledge is on the other hand implicit to the model's adaptation process, as farmers favor actions aligned with their strategy as long as it proves successful in maximizing utility. The coding was validated by repeating the process at different points in time. The results of the qualitative analysis were complemented by descriptive statistics based on the quantitative results.

Table C1 – Values identified in interviews and clustered under four over-arching groups adapted from the Theory of Basic Values framework of Schwartz (2012).

Openness to change (vs. maintain tradition)		**Self-transcendence (vs. self-enhancement)**	
-Dynamism -Experimentation -Innovation -Risk	-Habit -Tradition -Lifestyle (strategy) alignment -Risk aversion	-Conservation (resources – water, soil – heritage: inherently important to preserve)	-No conservation (resources –water, soil – not important / undesirable, consumption is important for individual survival)
Collaboration (vs. autonomy)		**Ambition (profit maximizing vs. satisficing)**	
-Openness to learning (collaboration)	-Independence (autonomy, flexibility, reliance on own experience) - Non-conformity	-High profit ambitions (maximize productivity)	-Low profit ambitions (satisficing, resigned – maintenance of current conditions)

- **Overview, Design Concepts, Details and Decision (ODD + D)**

Table C2 – Overview, Design concepts, Details and Decision (ODD+) protocol (Müller et al., 2013) description of the ABM.

		Model description
(I) Overview	I.i Purpose	The model is based on a case study of farm system dynamics in Romagna, Italy, exploring processes of transformational adaptation to climate change in a drought-prone Mediterranean area. The model and modelling results are primarily designed for individuals in research and practice interested in farm-level drought adaptation dynamics under climate change. The model specifically addresses three research objectives: (1) To quantify how farm-level adaptations in Romagna are likely to be driven by changing climate conditions, farmer decision-making behavior and water policies in the future (2) To evaluate the extent to which implemented adaptations represent transformations (3) To assess the impact of implemented transformational adaptations on future farm structure and wider socio-ecological change in Romagna
	I.ii Entities, state variables, and scales	The model is spatially explicit. Each patch (grid cell) represents a 5ha unit comprising (part of) a field within the agricultural extent (251120 ha) of 58 municipalities in the provinces of Ravenna, Forli-Cesena and Rimini. The ABM includes four different entities: (1) farmers, (2) fields, (3) patches, and (4) a global environment involving biophysical, demographic, economic and policy factors acting as the exogenous drivers to the model's processes. Both farmers and fields are coded as agents and farmer attributes include the aggregate characteristics of their respective fields, thus also representing farms. The model simulates dynamics from the year 2017 to 2050; each new year begins with a reading of cumulative soil wetness for the months of January and February and proceeds with each time-step representing a 10-day interval running throughout the annual irrigation season (lasting from the beginning of March through to the end of October)
	I.iii Process overview and scheduling	The model's process overview and scheduling is outlined in detail in **Table C3**. The model begins by updating farmer age, identifying which farmers retire and pass their land onto successors, sell it to a newcomer farmer or place it for sale on the market. Cumulative soil-wetness is then updated at each 10-day time-step throughout the year's irrigation season, determining whether fields see sufficient water or witness drought-induced damage to production. At the end of the irrigation season, farmers re-open any disused irrigation sources present on damaged fields, evaluate whether their aspired profits have been met, and update their drought risk perception. They then calculate the utility associated with each potential adaptation, based on whether the adaptation aligns with their pursued farming strategy and on its estimated monetary return on investment. Farmers only adapt if they

		perceive drought risk, and are more likely to adapt by selecting the adaptation with the highest utility if they have a low threshold for engagement in adaptation and don't see further biophysical, monetary or social constraints. The implemented adaptation may involve a substantial restructuring of the farming system, in which case farmers have undertaken a transformational adaptation and may update their production type and/or farming strategy. Following the implementation of (transformational) adaptations, farmers update additional characteristics (e.g. savings, new crop production, etc.), while regional variables relating to farm structure, annual agricultural revenues and irrigation withdrawals are recorded. The year ends with the implementation of rotation plans for open field crops. Based on the scenario selected in the interface at the beginning of each simulation, the model implements a different climate, irrigation water availability, subsidies, regulations, or prevailing farmer attitudes and values during model initialization
(II) Design Concepts	II.i Theoretical and Empirical Background	The model was constructed from a combination of theory and analysis of real-world observations. The analysis of field interviews undertaken with farmers and key informants in the case study area provided insight on both the adaptation decision-making process and the identification of influential internal and external characteristics. We identified distinctive farmer goals: some farmers wished to maximize profits, while others opted for a satisficing approach (Gotts et al., 2003), and farmers expressed a desire to pursue different farming strategies. Additionally, farmers expressed different attitudes and values as motivations for pursuing different strategies and adaptations. We categorized the identified values and farming strategies within established frameworks, notably the Theory of Basic Values (Schwartz, 2012) and the European categorization of farming strategies outlined in Ploeg and Roep (2003). We adapted the Modelling Human Behavior Framework (Schlüter et al., 2017) and the Model of Private Proactive Adaptation to Climate Change (Grothmann & Patt, 2005) to structure our socio-cognitive model of decision-making and incorporate the central influence of drought risk perception. Secondary sources and interview results were used for parameterization of the identified influential internal and external characteristics. Secondary data including census data and spatially-explicit climate projections. Lack of data availability led to the omission of some of the stated relevant internal or external characteristics expressed in interviews (see SI)
	II.ii Individual Decision Making	Decision-making in the model only takes place at the individual, farmer level, as institutions are modelled as non-responsive exogenous drivers to the model's processes. The object of farmer decision-making regards whether or not to engage in adaptation, and the selection of which adaptation to undertake. A farmer's evaluation of their drought risk perception strongly determines whether or not they choose to engage in

		adaptation. Drought risk perception is determined by whether a farmer is concerned about climate change (perceived probability of drought), and whether their aspired profits have been met over the past year following any drought damage (perceived severity of drought). Aspired profits are dependent on a farmer's age and successorship, as farmers grow older and lack successorship, their ambition to maximize profits decreases, and they instead become satisficers. Farmers who do not perceive any drought risk will not engage in any adaptation. All farmers who decide to engage in adaptation will select the adaptation which maximizes their utility, i.e. the adaptation with a higher estimated return on investment and alignment with their strategy. Farmers however don't have complete information regarding costs and benefits of potential adaptations, meaning some chosen actions may prove to be less effective at increasing profits than anticipated, or may turn out to not be feasible given certain external circumstances (e.g. spatial factors such as land availability, see following sections on Sensing, and Prediction). Values and attitudes further encourage or inhibit the selection of adaptations, and determine whether a farmer has a low or high threshold for engaging in adaptation. Values and attitudes are assumed to be static and not influenced by social networks or other exogenous forces. Temporal aspects play a role as cumulative soil-wetness interacts with crop growth stages and implemented adaptations induce long-lasting changes to a farmer's assets and goals
	II.iii Learning	Farmers change their decision rules over time as a consequence of experience. If a farmer's current strategy has proved successful in the past, the farmer will have met their aspired profits and be less inclined to change their strategy. The opposite occurs if farmers have not met their aspired profits. A failure to meet aspired profits results in farmers temporarily increasing their perception of drought risk. Collective learning is not implemented in the model
	II.iv Individual Sensing	Farmers are assumed to have complete and accurate knowledge of their own farm's characteristics. They utilize this information, alongside information on investment costs and annual profits from potential adaptations, to estimate the return of investment of the different adaptation options. Farmers do not hold information on short or long term climate forecasting, their estimation of future farm profits or benefits from investing in irrigation may therefore prove to be erroneous as a result of changing climate. Farmers have accurate knowledge of their neighbor's crop production, yet are not aware of their neighbor's interest in expanding irrigation or purchasing / selling land while they are deliberating on which adaptation to invest in; they only gain information on these aspects once they commit to undertaking respective adaptations. Farmers are all additionally assumed to be accurately aware of exiting subsidies and costs and profits

		associated with each adaptation. We do not assume any (cognitive) costs associated with gathering information
	II.v Individual Prediction	Every year, farmers estimate the return on investment from the eventual implementation of each of the seven adaptations. These estimates utilize a farmer's knowledge of their current farm characteristics, earnings, and expected investments costs and yearly profits from the adaptations. If a farmer's current strategy has proved successful in the past, the farmer will have met their aspired profits and be less inclined to change their strategy. These predictions may turn out to be inaccurate as farmers assume no barriers to the implementation of adaptations, and may assume maximum return on investments (i.e. farmers assume maximum productivity when estimating new profits from crop change). Farmers which have experienced significant drought-induced damage to production in the past or are concerned about climate change have a high drought risk perception, implying an expectation of droughts to occur frequently and severely in the future, therefore increasing their likelihood of adapting
	II.vi Interaction	Direct interaction between farmer agents occurs only when neighboring farmers jointly consider investing in new, shared irrigation infrastructure. Indirect interactions occur as farmers sell and purchase land within their neighborhood (limiting / enabling other farmers to engage in land purchase), or as farmers choose to engage in crop change, due to farmers limiting their choice of crop production to that of their neighboring farmers
	II.vii Collectives	Collectives can emerge as neighboring farmers jointly invest in new, shared irrigation infrastructure. Farmer cooperatives are not explicitly represented and only influence farmer decision-making by providing additional subsidies for efficient irrigation systems to member farmers
	II.viii Heterogeneity	The farmer population is heterogeneous as farmers hold different characteristics. Farmers which pursue the same strategy, undergo similar production, or operate within the same municipality have a higher probability of holding similar characteristics. These differences in a farmer's goals, values, attitudes and assets result in different decision-making processes and/or preferences
	II.ix Stochasticity	Some characteristics of the model entities were randomly assigned to their respective agents or patches. Processes explored through the ABM also involved some degree of stochasticity, notably in the following processes: determination of the age of newcomer or successor farmers; presence / absence of a successor farmer or new farmer willing to purchase the farm; aspired crop when considering crop change; broadening profits; likelihood of a high estimated return on investment value from uptake of deepening activities; likelihood of a high or low threshold for engagement in adaptive action; water conservation values (manifested in willingness to invest in low water demanding crops or high efficiency

		irrigation). See the sub-model descriptions in **Table C3** for further details
	II.x Observation	Model outputs were collected through NetLogo's BehaviorSpace tool or exported through GIS functions. Key outputs are additionally displayed in the model interface. The selected outputs address the research aims and therefore refer to changing characteristics of the local farmer population (production type and strategy), implemented (transformational) adaptations, and changes to regional irrigation water withdrawals, agricultural revenues, production areas and number of active farmers. GIS outputs identify drought-damaged areas, irrigated areas by source, cultivated areas, and areas undergoing crop change under each scenario
	II.i Implementation Details	The model was developed in NetLogo v. 5.3.1 (Wilensky, 1999) and uses the GIS and CSV extensions, and will be made available on the departmental data repository webpage of the corresponding author upon publication of the manuscript
(III) Details	III.ii Initialization	Details the process of parameterizing model variables, and a list of model variables and their reference values at initialization (or, where relevant, following the first year of simulation) are provided in the online SI. The values of some variables at initialization change based on the climate, behavioral or water policy scenario selected in the interface
	III.iii Input Data	The model reads external CSV files on climate variables (according to the specific time period and RCP scenario being explored) as well as external GIS files with information on initial field boundaries, farm(er) locations, crop production, watershed boundaries and irrigation water sources and availability
	III.iv Sub-models	See **Table C3** for details on the sub-models

Table C3 – Outline of the ABM's sub-models following initialization, providing details and assumptions implemented for each command specified in the model's NetLogo code. Described in accordance with the ODD + D protocol template (Müller et al., 2013).

Sub-model	Command	Command description
Sub-model 1	Tick	-Time is updated by 1 unit (i.e. 10 days)
	Update-age-quitting	*[Checks time-step and only runs the command if within the first time-step of the year]* -Farmers age by one year and update their age class -If a farmer reaches retirement age and a successor is present, the farm is passed on to the successor farmer which inherits all characteristics with the exception of age, memory of initial conditions (re-set to reflect their current state) and probability of having a successor -If no successor is present, farmers evaluate whether there is a newcomer farmer who is willing to purchase their farm. If such a farmer is present, it will purchase the farm and undergo the same updates as a successor farmer; instead of inheriting savings these will however be re-assigned -If no newcomer farmer is willing to purchase the farm, the farmer quits the simulation and the farm is placed on the market for future purchase by other farmers
	Determine-season-length-kc	-Fields update their crop-kc value according to the current season and crop type
	Starting-wetness	*[Checks time-step and only runs the command if within the first time-step of the year]* -The model reads watershed-specific climate data on 2-month cumulative reference evapotranspiration and precipitation values relative to the months of January and February for the respective year and RCP scenario selected in the interface -Fields update their cumulative precipitation and reference evapotranspiration values from the selected climate data; reference evapotranspiration is multiplied by the crop-kc value -Fields update their starting cumulative soil wetness values by subtracting their starting crop evapotranspiration value from their starting precipitation value
	Climate-data	-The model reads watershed-specific climate data on 10-day cumulative reference evapotranspiration and precipitation values for the respective time-step (starting March 2017) and RCP scenario selected in the interface
	Calculate-wetness	-The model reads the 10-day mean river discharge-values for the respective time-step and RCP scenario

		selected in the interface. If the river run-off levels are below the established critical threshold, all irrigation amounts are set to 0 -Patches update their cumulative precipitation and reference evapotranspiration values from the selected climate data; reference evapotranspiration is multiplied by the patches' crop-kc value -Patches within irrigated fields calculate (1) the amount of irrigation water they can withdraw from their sources for this respective time-step, adjusting their quota based on the respective irrigation system efficiency of their field (i.e. less efficiently irrigated fields adjust their irrigation quota to withdraw more water), and (2) the amount of irrigation water which will be available to the field's crops in this time-step following irrigation system losses. Fields irrigated by LRIC sources calculate their quota by dividing the maximum volumetric capacities of each district by its initial irrigated area, and allocating the per hectare irrigation volumes evenly throughout the field's respective crop growing season. For fields irrigated through private concessions or newly established collective LRIC sources the maximum potential irrigation volumes are determined according to crop-based annual irrigation estimates -Fields update their soil wetness value by subtracting their crop evapotranspiration value from their precipitation value, and adding any irrigation inputs -Soil-wetness values throughout the irrigation season are added to calculate cumulative soil wetness; if this reaches below -40mm within its growing season, the field becomes damaged by drought
	Emergency-adaptation	-Farmers choose to re-open any disused private water sources present on fields which have been damaged by drought – the opening of these water sources only becomes effective from the beginning of the following year. This decision is therefore assumed to only ever be taken reactively (i.e. following the experience of drought damage), and once re-opened, the formerly disused private water sources remain open for the remainder of the simulation
Sub-model 2	Recalculate-initial-volume	*[Checks time-step and only runs if at the end of the first year of the simulation, i.e. 2017]* -Cultivated fields record the hypothetical, initial irrigation water withdrawal, ignoring any disruptions from irrigation closures or the cultivation of autumn-winter crops. Fields under a 3-year rotation plan estimate their 3 year mean irrigation volume consumption and record this as their starting irrigation volume consumption

	Set-strategy-action	*[Checks time-step and only runs the commands of "sub-model" 2 and 3 if the end of the irrigation season has been reached]* -Cultivated fields record their total irrigation water withdrawals by source throughout the irrigation season. The annual hypothetical irrigation use is also recorded, ignoring any disruptions from irrigation closures or the cultivation of autumn-winter crops -Farmers record any (transformational) adaptation(s) which has/have taken place in the previous year -Farmers update their adaptation preferences to align with their (newly) pursued strategy. Only farmers which value openness to change and pursue expansionist or deepening strategies consider crop change as a preferred action. While farmers only "pursue" one strategy at a time, they do not however halt ongoing diversification activities related to previous strategy implementation, i.e. diversifying farmers opting for a productivist (expansive or contractive) strategy do not cease their diversification activities, they only change their preferences for future action. This reflects interview results which showed farmers implement multiple strategies simultaneously and, if unsatisfied with their current diversification strategy, tend to modify actions within their diversification type rather than altogether halting diversification activities. If farmers have undergone multiple strategy changes in the previous time step (e.g. started diversification and changed to expansionist strategy following past changes to irrigation use), non-diversifying strategies will prevail in the assignment of preferred actions
	Update-profit	-Fields which have witnessed drought induced damages to production update their revenue (30% reduction) -Irrigated fields calculate their annual irrigation costs depending on their irrigation source -Farmers update their annual profits, accounting for field crop specific costs and revenues, irrigation water costs of their irrigated fields, subsidies received for deepening activities and profits received from broadening activities -Farmers adjust their savings based on the profits or losses made throughout the year
	Determine-aspired-income	-Farmers determine their aspired agricultural profits; if they are above 40 years of age and lack successorship, they are satisfied with making 65% of their maximum potential agricultural profit (related to crop related revenues and costs only, excludes water costs) -Farmers determine whether their aspired agricultural profits have or have not been met

	Calculate-risk-appraisal	-Farmers update their drought risk perception based on their concern for climate change and whether their aspired agricultural profits have or have not been met as a result of drought damage. The two components of drought risk perception are equally weighted, resulting in a potential value of either 0, 0.5 or 1
	Calculate-eventual-profits	-Farmers then estimate the return on investment they would gain from undertaking each of the 7 adaptations by dividing respective estimated annual profits by estimated investment costs, as follows: *(1) Purchase land:* -Farmers are assumed to only purchase a maximum of one field per year. Farmers not open to changing their production type estimate potential profits from land expansion by assuming the purchase of a 10 ha field (mean field size in the region) whose per hectare profit is equal to their farm's current average value. The cost of land throughout the region is a uniform per hectare value; investment costs are calculated by multiplying this value by 10 ha. If the farmer has enough savings to cover the investment costs, the estimated return of investment for this action is calculated by dividing the annual estimated profits by the investment costs, if savings are insufficient the potential return on investment is set to 0 -Farmers open to changing their production type follow the same calculation, but estimate the potential change to annual profits differently. Instead of assuming an extension of current annual profits from the purchase of a new 10 ha field, they select the per hectare profits (excluding irrigation costs) of a random crop grown in the region, and also multiply this value by 10 ha. Deepening and non-deepening farmers have different estimations of crop profits reflecting the different production practices or market values involved (*2) Expand irrigation water source:* -Farms which are already fully irrigated will not gain additional profits from investing in this action and therefore automatically assign it a potential return on investment value of 0 -Farms which are not (fully) irrigated calculate the potential annual profits gained from this action by (1) estimating the additional annual revenue it would bring by avoiding drought damage on all their rain-fed fields (regardless of whether these are neighboring), equal to 30% of their mean revenue, and (2) estimating the additional annual costs it would bring through increased irrigation water costs (dependent on the mean crop-based irrigation volume demands and total size of rain-fed fields). Investment costs are

	calculated based on the cost of constructing the new water source and the cost of installing new irrigation systems on all rain-fed fields (assuming sprinkler systems). Farmers who are members of cooperatives (i.e. do not value autonomy and are not undertaking deepening activities) receive a discount on the cost of irrigation systems. The return on investment is calculated by subtracting estimated annual irrigation costs from the estimated avoided damage to crop revenue, and dividing this value by the investment costs. If the farmer's savings are below the investments costs for this adaptation, the return on investment value is set to equal 0 *(3) Change crop production:* -Farmers estimate the financial benefits of crop change by considering a change in production to the field which has resulted in the lowest profits throughout the past irrigation season (accounting for drought induced damages) -Farmers randomly select a crop which can earn them a higher potential profit than that of the field they are considering for change. The crops considered vary depending on whether the farmer: (1) has pursued a deepening strategy, resulting in different crop profits from non-deepening farmers due to differences in production or market value, (2) values water conservation or does not have access to irrigation and therefore only considers transitioning to crops with low irrigation water demand (estimated annual irrigation needs < 2000 m^3/ha), and (3) does not value openness to change production and therefore only considers transitioning to permanent crops if currently a permanent crop specialist, or herbaceous crops if currently a horticultural or field crop specialist (mixed cropping farmers which are not open to change select crops which are of the same type as the ones the farmer is replacing, i.e. permanent or herbaceous). Farmers hoping to replace an herbaceous field which is part of a rotation plan don't consider investing in other rotating crops and only consider high water demanding vegetables and/or permanent crops. Differences in profits which may arise from changes to irrigation water costs are ignored -Investment costs are crop-specific costs related to the conversion towards the new crop (ground preparation, planting, etc.). Farmers which transition from permanent to herbaceous costs only incur crop removal costs. Farmers which transition between herbaceous crops do not incur any investment costs -Farmers calculate return on investment for this adaptation by subtracting their current field's

	maximum potential profits from the maximum potential profits of the chosen aspired crop (excluding eventual changes to irrigation costs), and dividing this value by the crop specific investment costs. If the investment costs of the aspired crop are 0, the estimated return on investment value is automatically set to equal 1.1 (reflecting higher annual profits than investment costs). If the farmer's savings are below the investments costs for this adaptation, the return on investment value is set to equal 0 *(4) Upgrade irrigation system:* -Only irrigating farmers which haven't already upgraded their irrigation systems and are receiving water through metered sources or value water conservation will gain additional "profits" from investing in this action, other farmers are therefore automatically assigned a potential return on investment value of 0 -Annual profits from upgrading the farm's existing irrigation system are calculated by calculating the difference in metered irrigation water costs which would arise by changing the total amount of irrigation water withdrawn as a result of an average increase in irrigation system efficiency for all of the farm's irrigated fields which are not already at maximum efficiency (we therefore assume farmers maintain the same type of irrigation system, but strive to increase its efficiency) -Investment costs reflect the costs of installing new micro-irrigation systems across all the irrigated fields which are not already using such systems (micro-irrigation used as proxy as most expensive) -Farmers who are members of cooperatives (i.e. do not value autonomy and are not undertaking deepening activities) receive a discount on the cost of irrigation systems -The return on investment is calculated by dividing estimated increase in profits, through a reduction in the cost of irrigation water, by the investment costs. If the farmer's savings are below the investments costs for this adaptation, the return on investment value is set to equal 0 *(5) Start deepening activities:* -Deepening activities are subsidized and therefore do not hold investment costs; values are instead used as proxies for evaluating the "profitability" (i.e. "gains") from implementing the action, as farmers are in this case motivated by values alignment. Farmers which both value autonomy and environmental conservation have the highest likelihood of valuing investment in deepening

	activities and therefore of being assigned a potential return on investment value of 1.1 (reflecting higher annual profits than investment costs). These values are relevant to activities involving the direct sale of farm produce and/or organic and integrated farming. If farmers do not value autonomy nor environmental conservation, they hold a lower probability of valuing investment in deepening activities, and therefore of holding a potential return on investment value of 1.1 -If farmers are already undertaking deepening activities, their potential return on investment value is automatically set to equal 0 -We assume farmers don't disengage from diversification activities, assuming scaling down of all farm-based activity only occurs through land sales *(6) Start broadening activities:* -Annual profits gained from investing in broadening activities are calculated based on the farm's annual agricultural revenue – above a certain threshold, the estimated annual profits from broadening activities are assumed to be lower, assuming a trade-off in time and capital between broadening and agricultural activities which would be more difficult to surpass for farmers with a higher investment in their agricultural activities. Farmers with agricultural revenues below this threshold are randomly assigned higher estimated annual profits from broadening within a specified range -Investment costs are directly proportional to the estimated annual profits and account for EU subsidies and a maximum ceiling -Farmers calculate their estimated return on investment from this adaptation by dividing estimated annual profits by the estimated investment costs. If the farmer's savings are below the investments costs for this adaptation, the return on investment value is set to equal 0 -If farmers are already undertaking broadening activities, their potential return on investment value is also automatically set to equal 0 -We assume farmers don't disengage from diversification activities, assuming scaling down of all farm-based activity only occurs through land sales *(7) Sell land:* -The estimated return on investment value for land sale is set to equal that of the adaptation with the highest estimated profitability (excluding estimations for farm expansion), interpreting the gains made from selling land as opportunities for future investment in other actions. If all other adaptations have an estimated profitability of 0, the estimated profitability of shrinking is automatically set to equal 1.1.

		Farmers are assumed to only sell a maximum of one field per year -All return on investment values which hold a value > 1.1 re-set their values to equal 1.1 and all values below 0 are given a value of 0 -Return on investment (i.e. "profitability") values are normalized to give each action an estimated return on investment value ranging between 0 and 1
	Selection-action	-Farmers calculate the utility of each adaptation by summing its profitability (value range between 0 and 1) and alignment with their farming strategy (value of 0.5 if the adaptation aligns), and add these to the farmer's own drought risk perception (DRP) (value of either 0, 0.5 or 1) -Farmers are assumed to only undertake a maximum of one adaptation per year, and select the adaptation with the highest utility; if two or more adaptations hold the same utility value, one adaptation is randomly chosen between the actions -Farmers determine their threshold value for engaging in action. If they value openness to change, they set their threshold to equal 2. If they do not value openness to change they run a 50% probability of holding a threshold value of 2 or 2.1. Farmers whose selected adaptive action's utility value summed with their drought risk perception value surpasses their threshold for change proceed to its implementation / evaluate its implementation [action implementation]. The threshold values of 2 or 2.1 imply farmers can only engage in adaptation under the following conditions: 1) DRP = 0.5, adaptation threshold = 2 and an adaptation is found which both matches the farmer's strategy and has the highest estimated ROI 2) DRP = 1, adaptation threshold = 2.1, and an adaptation is found which both matches the farmer's strategy and has an estimated ROI > 0.5 3) DRP = 1 and the adaptation threshold = 2
Sub-model 3	[action implementation]	-These commands only run if respectively selected as part of the "selection-action" command in sub-model 2: *[consider-area-expansion]* -Farmers identify any fields available for sale within a radius at an affordable price; farmers not open to change production type limit this identification to fields which match their primary production (permanent crops vs. herbaceous crops); mixed cropping farmers not open to change production type opt for the identification of permanent or herbaceous crop fields depending on which is most prevalent within their neighborhood

	-If more than one field is available for sale matching the farmer's criteria, farmers choose to purchase the field with the potential to yield the highest profit -Farmers purchase the selected field, updating their total farm size and savings following the deduction of purchase costs -Purchased fields update their expected costs, revenues and deepening subsidies based on whether their farmer is or is not undertaking deepening activities. All newly purchased fields growing herbaceous crops are set to undergo a rotation plan -If no fields are available for sale within the neighborhood, no adaptive action is implemented by the farmer which proceeds to the "reset-values" command *[consider-new-ws-cooperate]* -Farmers check if their rain-fed fields are in proximity of existing LRIC irrigation districts, enabling the expansion of new LRIC sources -If fields are in proximity of existing LRIC districts, farmers make it known to neighboring farmers that they are open to collectively invest in a new irrigation source for those selected fields -If at least 10 rain-fed fields each owned by a different interested farmer are in proximity of each other, the farmers choose to collectively invest in the construction of the new irrigation source to provide water to these fields -Farmers invest in efficient sprinkler irrigation systems for the newly irrigated fields. Farmers belonging to cooperatives receive a subsidy and have lower costs -Fields update their irrigation status and irrigation systems and efficiency -Farmers update their savings, subtracting investment cost -The model does not assume construction delays, and the water source is able to provide water from the beginning of the following year's irrigation season -If the farmer's rain-fed fields are not in proximity to existing LRIC districts, or if there are not a sufficient number of other farmers interested in investing in a collective source, no adaptive action is implemented by the farmer which proceeds to the "reset-values" command *[consider-crop-change]* -Farmers check if their desired crop for replacing current production on their least profitable field (selected within the "selection-action" command in sub-model (2) is cultivated within the neighborhood (simulating suitability for crop growth)

		-If the crop is being cultivated within the neighborhood, farmers update their savings to adjust for crop conversion costs, if any -The field selected for undergoing crop change updates its crop type and crop-based attributes (costs, revenues, crop-kc value, etc.). The model does not assume any differences in productivity based on age of permanent crops -If the crop is not being cultivated within the neighborhood, no adaptive action is implemented by the farmer which proceeds to the "reset-values" command *[consider-i-s-change]* -Irrigated fields with sliding irrigation upgrade to high efficiency sprinkler systems -Irrigated fields with low-efficiency sprinkler or micro-irrigation systems upgrade to higher efficiency versions of the same systems -Farmers update their savings following deduction of investment costs (cheaper for cooperative farmers) *[consider-area-reduction]* -Farmers sell their field yielding the lowest profits (subject to production damages that year), update their savings through incomes from land sale and update their farm size -If farmers have sold their only field, they quit the simulation as they no longer own any land to farm. The model records the number of farmers which have quit farming throughout the year -The sold field updates its ownership status indicating it is available for sale *[consider-diversify-broaden]* -Farmers update their savings, following the deduction of broadening investment costs, and their strategy to a broadening strategy, ceasing their expansive or contractive strategy if either of them was being pursued -Farmers record a transformation has taken place through the uptake of a new strategy *[consider-diversify-deepen]* -Fields update their crop-specific costs, revenues and subsidies to match those associated with deepening farming activities -Farmers update their strategy to a deepening strategy and cease their expansive or contractive strategy if either of them was being pursued -Farmers record a transformation has taken place through the uptake of a new strategy
	Reset-values	-Annual irrigation water withdrawals and consumption are calculated for the region for each type of irrigation water source

		-Annual agricultural revenues are calculated for the region for each crop class -Fields update certain values prior to the beginning of the following year (clear annual irrigation consumption and cumulative wetness values, re-set profits to non-damaged levels, open formerly disused private water sources if farmers had chosen to re-open them following damage to field) -Farmers update certain attributes prior to the beginning of the following year (clear attributes related to the implementation of their selected adaptations) -Newly irrigating farmers concerned about climate change update their water conservation value determining whether they will / will consider investing in high water demanding crops and will / will not consider investing in efficient irrigation systems despite investing in fields irrigated by unmetered sources in the future -A farm's annual hypothetical irrigation withdrawal values are summed to those of the previous year; every three years, a 3 year mean value is calculated -Farmers which have undergone changes in farm size or changes to crop production calculate the total standard output of their production and the respective share comprised by permanent crops, horticultural crops or field crops. They then calculate whether their production type has changed by calculating whether 2/3rds of their total standard output is comprised by a different production than that of their current type (farmers which don't hold a 2/3rd majority standard output value for any crop type are considered mixed cropping farmers), complying with the EU's Farm Accountancy Data Network classification. If this is the case, the farmer changes farm production type and records they have undergone transformational change. New horticultural specialists stop rotations on their grain and vegetable fields; newly purchased vegetable fields by horticultural specialists also stop undergoing a rotation plan. A farmer which transitions from a horticultural specialist to any other production type will on the contrary begin a rotation plan on all their herbaceous crop fields
	Crop-rotation	-Non-horticultural specialists which had undergone crop change and decided to replace a herbaceous field with a high water demanding crop but did not transition to a horticultural specialist decide to no longer undergo this crop change (as it would be ineffective due to rotation) -Cultivated fields belonging to the autumn-winter crop class undergo crop rotation and are replaced by

		either grains or vegetables, fields belonging to grains and vegetable crops which are undergoing a rotation plan are replaced by alfalfa production, while alfalfa is replaced by the production of autumn-winter crops (these crop transitions don't take into account whether fields are irrigated or rain-fed) -Field attributes relating to crop-specific values (revenues, costs, crop-kc, etc.) are updated accordingly following the crop change
	Change-strategy	-Farmers evaluate changes to their farm size and hypothetical irrigation volume withdrawals, the latter compares whether their 3-year mean value differs from their initial conditions (to even out differences due to crop rotations). If changes represent an increase or decrease of 1/3rd of their original values, farmers record they have undergone a transformation (in scale or input) (complying with the definition of Vermeulen et al. (2018)). If this transformation represents an increase in farm size and use of irrigation, and the farmer was not currently pursuing an expansive strategy, the strategy if changed to expansive and a transformation (relative to strategy change) is additionally recorded. The farmer ceases to pursue a contractive strategy if this was previously the case. The same process occurs linking transformational reductions in farm size and irrigation use to a change towards a contractive strategy. If both irrigation and scale surpass transformational threshold but in opposing directions (expansive and contractive), the direction defined by scale prevails for defining eventual strategy changes. Farmers which have undergone relevant transformation re-set their initial farm size and/or hypothetical irrigation withdrawals to match their latest conditions (hypothetical irrigation withdrawals are calculated by running the recalculate-initial-irrigation-volume function)

D. Chapter 5

A selection of key Supplementary Information is hereby provided. For a comprehensive overview of this chapter's Supplementary Information, please refer to the forthcoming online version of the published article this chapter is based on.

- **Review and selection of sustainable farm-based adaptations**

We based the identification of sustainable farm-based adaptations suitable to croplands of the Mediterranean Basin on the findings of recently published reviews synthesizing known or potential agricultural adaptations for the region (Aguilera et al., 2020; Fraga et al., 2012; Harmanny & Malek, 2019; Iglesias et al., 2012; Iglesias & Garrote, 2015; Moriondo et al., 2010; Olesen et al., 2011). We complemented these publications with two, more comprehensive, studies, notably presenting a global review of climate-smart agricultural practices (Scherer & Verburg, 2017), and a broad typology of agricultural adaptations to climate change (Smit & Skinner, 2002). From all the adaptations identified in the reviewed literature, we were interested in selecting only farm-based adaptations which involved physical changes to a farm's land or water management, i.e., its crop, soil, or water resources. This choice was motivated by a desire to limit the exploration of adaptations to those which fell under a farmer's decision-making power, and to adaptations with known spatial variability, whose implementation depends both on socio-economic and biophysical attributes. We undertook a first screening round and excluded adaptations which (1) did not directly or explicitly involve farm-level physical land or water management changes (e.g., securing climate risk insurance), (2) addressed livestock farming and not cropland farming, and (3) only involved the adjustment of timing or intensity of management.

In the second screening round we made a final selection of which adaptations to include in our spatial assessment. We sought to ultimately select adaptations with potential to simultaneously mitigate the two main climatic challenges identified for our selected crop productions (notably drought and heat stress), and with wide potential applicability throughout the region (i.e., not specific to certain productions only). To provide a comprehensive evaluation of adaptation potential, we additionally sought to select adaptations relevant to different components of a farming system, notably its soil, water, or crop sub-system. For each sub-system, we aimed to select one adaptation aiming for incremental change, and one adaptation aiming for transformational change (likely to be required in areas with more substantial climatic impact). Further considerations involved the availability of data to enable the spatial suitability assessment. Details on this second, final, selection round are outlined below:

- For soil-based adaptations, we identified introducing organic inputs, implementing reduced or zero tillage practices, mulching or other types of permanent soil cover, and the introduction of terracing and other modifications to field topography as the main types of adaptation. We focused on mapping the suitability of minimum tillage (hereby referring to both reduced tillage and no-tillage practices) as the *incremental* strategy, and the more comprehensive implementation of Conservation Agriculture (CA) (which incorporates minimum tillage practices (i.e., direct seeding and/or fertilizer placement) with permanent soil cover and the implementation of diversified crop productions, including rotations and relay cropping) (FAO, 2011) as the *transformational* strategy. This selection was determined by spatial data availability and a greater identified potential to address climate change impacts across a broad range of farm types.
- For water-based adaptations, our literature review identified three different adaptation categories, notably (1) irrigation expansion (based on the construction of new sources including wells, reservoirs, and desalination plants), (2) irrigation reduction, and (3) changing irrigation management to increase water use efficiency (largely through the adoption of drip irrigation). As increasing demands for irrigation are forecast for the region, and surface irrigation currently represents the prevailing irrigation system (Daccache et al., 2014), we narrowed our investigation of adaptation suitability to the substitution of surface or sprinkler irrigation with drip (as the *incremental* strategy), and the transition from rain-fed to irrigated

agriculture (as the *transformational* strategy), identifying these two adaptations as those with the greatest potential for implementation. We conceptualized sustainable irrigation expansion as expansion that does not compromise future freshwater ecosystems due to streamflow reductions (Rosa et al., 2020).

- For crop-based adaptations, the literature referred to the introduction of cover crops, crop rotations, hedges or on-farm woodland, agroforestry, or changes to crops with higher climatic resilience (ranging from implementing new or local varieties, to changing crop species). We selected variety change as the *incremental* strategy, and crop change (i.e., changing crop species) as the *transformational* strategy, as the other adaptations were less widely applicable and/or showed potential to mitigate fewer climatic impacts.

- Review, selection, and processing of proxies for the adaptation suitability mapping

We searched peer-reviewed literature on Google Scholar to identify hard constraints, soft constraints, and enablers to the implementation of our selected adaptations (i.e., their "adoption factors" and "exclusion factors"). We searched for key words relating to each of the adaptations, coupled with "determinants" or "drivers", "enablers", or "constraints", and names of countries within the Mediterranean Basin. We additionally searched for global review papers synthesizing determinants of the adaptations, and for studies similarly aiming to map their potential suitability. The mapping of suitability for conservation agriculture and reduced tillage was based on the global mapping analysis of conservation agriculture of Prestele et al. (2018), as literature from the Mediterranean identified the same adoption factors, relevant for both minimum tillage and CA (**Table D1**). **Table D1** lists the resources for the identified adoption factors for which spatial proxies could be sourced.

The following adoption / exclusion factors were additionally identified in the literature but were excluded from the suitability analysis either due to a lack of suitable spatial data proxies, or because the literature suggested mixed and inconclusive evidence:

- Soil-based adaptations: risk attitudes and cultural norms of farmers, high rates of weed infestation, presence of subsidies or incentive programs, and presence of stakeholder promotion networks to demonstrate benefits and provide knowledge resources (Kassam et al., 2012; Morugán-Coronado et al., 2020; Ruiz et al., 2020).
- Drip irrigation: farm(er) characteristics including behavioral aspects (notably inclination to innovate, risk aversion and traditionalist preferences, (Alcon et al., 2019; Molle & Sanchis-Ibor, 2019)), age (Pronti et al., 2020), gender (Pronti et al., 2020), education (Jobbins et al., 2015), on-farm labor (Aridah, 2016; Jobbins et al., 2015; Kalpakian et al., 2014; Molle & Sanchis-Ibor, 2019) and neighborhood dynamics (Mourshed, 1996). External attributes referring to the existence of subsidies, regulations or (international) capacity building projects (Ameur et al., 2020; Jobbins et al., 2015; Kalpakian et al., 2014; Lasram et al., 2018; Molle & Sanchis-Ibor, 2019; Morita, 2016; Mourshed, 1996; Oulmane et al., 2020), as well as land fragmentation (Jobbins et al., 2015; Molle & Sanchis-Ibor, 2019) and type of water sourcing (Jobbins et al., 2015; Morita, 2016; Oulmane et al., 2019; Pronti et al., 2020; Varela-Ortega & Sagardoy, 2002).
- Irrigation expansion: policy (political stability, administration procedures, water metering, water pricing, extraction regulations and permits) (Molle & Sanchis-Ibor, 2019; Neumann et al., 2011; Wight et al., 2021), farmer norms, values and attitudes (trust, cooperation), gender equality and development (Piemontese et al., 2020).
- Crop-based adaptations: institutional constraints (including public investment in crop breeding programs), the genetic base of crops, risk aversion attitudes of farmers, education levels of farmers (Singh et al., 2020), social/professional networks of farmers (Goldberg et al., 2021), and proximity of farmers to niche supply chains promoting varietal innovation (Akimowicz et al., 2021).

Table D1- Adoption factors used for mapping each adaptation, literature supporting their inclusion, and respective spatial proxies.

Adoption factor (proxy)	Water		Soil		Crop	
	Drip irrigation	**Irrigation expansion**	**Reduced tillage**	**Conservation agriculture**	**Varietal change**	**Crop change**
Slope (%) (Fischer et al., 2008)	Surface irrigation is unsuitable on slopes >8%, flat areas are therefore less likely to be allocated to drip irrigation (Fischer et al., 2021)	Slope influences irrigated agriculture by altering workability of soil, fertility and accessibility of plots (Heistermann, 2006)				Different crops have varying degrees of suitability to different slopes (Fischer et al., 2021; Sys et al., 1993)
Median elevation (m) (Fischer et al., 2008)		Altitude is associated with different crop productions and climates which influence irrigation water requirements (Genius et al., 2014; Malek & Verburg, 2017)				
Soil properties (electric conductivity, exchangeable sodium percentage, calcium sulphate, calcium carbonate,	Sand and loamy sand soils, soils with excessive or somewhat excessive drainage, high electric conductivity, and calcium sulphate, as well as stony or rudic	Soil quality determines adoption of irrigation (Heistermann, 2006; Malek & Verburg, 2017; Piemontese et al., 2020)				Different crops have varying degrees of suitability to different soil conditions (Fischer et

soil texture, drainage, sand and clay content, cation exchange capacity (clay), soil pH, reference soil depth and/ or soil phase, coarse fragments, organic carbon content) (Fischer et al., 2008)	phases all hold severe constraints or are unsuitable to surface irrigation while being at least moderately suitable to drip under production of relevant crops. These areas are therefore more likely to be allocated to drip (Fischer et al., 2021)			al., 2021; Sys et al., 1993)
Soil erosion (global soil erosion by water, Mg /ha/year) (Borrelli et al., 2020)			Increased soil cover resulting from CA and minimum tillage results in reduced risk of soil erosion (Kassam et al., 2012, 2015; Montgomery, 2007; Porwollik et al., 2019)	
Aridity (global aridity index) (Trabucco & Zomer, 2009), (average annual temperature, °C) (Fick & Hijmans, 2017), (annual average potential evapotranspiration, mm) (Zomer et al., 2008))	Drip irrigation is often used in areas with arid and drought-prone conditions to limit water use and avoid likely higher irrigation costs. Projects or subsidy schemes promoting the use of drip are also most often situated in arid regions (Alcon et al., 2019; Daccache et al., 2014; Mourshed, 1996; Pronti et al.,	Arid environments have pushed development of irrigation (Malek & Verburg, 2017; Molle & Sanchis-Ibor, 2019; Neumann et al., 2011)	CA and minimum tillage can result in increased soil water holding capacity (Mrabet et al., 2012; Soane et al., 2012; WOCAT, 1992)	

	2020; Varela-Ortega & Sagardoy, 2002)			
Irrigation water availability (average groundwater table depth, cm) (Fan et al., 2013; Linke et al., 2019), (river volume, million m^3) (Lehner & Grill, 2013; Linke et al., 2019)		Water availability determines potential for further irrigation expansion (Heistermann, 2006; Neumann et al., 2011; Rosa et al., 2020)		
Crop type (crop irrigation system suitability and irrigation dependency) (International Food Policy Research Institute, 2019; Portmann et al., 2010)	Mediterranean high value fruit crops are suited to drip and less suited to other irrigation systems (e.g., surface and sprinkler), while other crops suitable to drip are also suitable to other irrigation systems and are therefore less likely to be allocated to drip (Daccache et al., 2014)	Crops have different water requirements and therefore different likelihoods to prompt the efficient implementation of irrigation (Heistermann, 2006)		
Access to irrigation (percentage area equipped with irrigation) (Siebert et al., 2013)				Access to irrigation is associated with greater crop diversification (Akimowicz et al., 2021; Goldberg et al., 2021)

Poverty (percentage of people living in poverty outside of urban centers) (CIESIN/IFPRI/CIAT, 2011; Elvidge et al., 2009)	Drip has high installation and maintenance costs only affordable to farmers with access to credit. Costs are also often not fully covered by existing subsidy schemes, which in turn also have strict and limiting access requirements (Alcon et al., 2019; Daccache et al., 2014; Foltz, 2003; Jobbins et al., 2015; Kalpakian et al., 2014; Oulmane et al., 2020)	Irrigation requires high costs (material and labor costs) (Neumann et al., 2011)	CA and minimum tillage machinery is costly and implementation potentially results in reduced yields in initial years (Chalak et al., 2017; Giller et al., 2009; Kassam et al., 2012; Pannell et al., 2014; Porwollik et al., 2019; WOCAT, 1992)	Farmers require capital to purchase new seeds and access markets, inputs and knowledge; wealthier farmers are also less risk averse, more willing to experiment with different productions (Akimowicz et al., 2021; Goldberg et al., 2021; Hassan & Nhemachena, 2008)
Access to knowledge and equipment (market accessibility index) (Verburg et al., 2011)	Drip irrigation maintenance is more technically demanding than for other irrigation systems. Access to extension agents and market areas is associated with higher rates of investment in drip through demonstrative exchanges and lower transaction costs (Alcon et al., 2019; Brouwer et al., 1988; Foltz, 2003; Jobbins et		CA and reduce tillage requires specialized equipment and/or know-how (Bonzanigo et al., 2016; Chalak et al., 2017; Giller et al., 2009; WOCAT, 1992)	Extension workers illustrate benefits of adopting different varieties (e.g. through field demonstration, distributions of mini-seed kits) and raise awareness on climate change impacts; facilitated market access enables purchase of new variety seeds and reduces transport and transaction costs (Akimowicz et al., 2021; Hassan & Nhemachena, 2008; Kassem et al., 2019; Singh et al., 2020)

	al., 2015; Mourshed, 1996)			
Farm size (dominant field size) (Lesiv et al., 2019)	Small farms are unlikely to be able to justify investment in drip irrigation, e.g., due to lower labor costs where drip can bring savings (Alcon et al., 2019; Bazza & Najib, 2003; Jobbins et al., 2015)	Small farms are less likely to be able to justify investments in irrigation (Molle & Sanchis-Ibor, 2019)	Higher implementation of CA and minimum tillage in large farms due to higher economic returns and ability to test implementation (Derpsch et al., 2010; Djender, 2020; Kassam et al., 2012; Loss et al., 2015; Pannell et al., 2014; Porwollik et al., 2019)	Small farms are less likely to implement variety changes (less likely to have available capital; less likely to have high training and education) (Akimowicz et al., 2021; Goldberg et al., 2021; Singh et al., 2020)
Land ownership (ease of registering property at national level) (World Bank, 2020)	Tenant farmers are less likely to have access to subsidies or credit loan schemes, and are less inclined to invest in land they do not own (Alcon et al., 2019; Foltz, 2003; Jobbins et al., 2015; Oulmane et al., 2020; Pronti et al., 2020)			

The suitability mapping for drip irrigation, crop and variety change, reduced tillage, and conservation agriculture all followed the same methodology, largely based on that of Prestele et al. (2018). As a first step, the spatial datasets identified as proxies for the adoption factors were masked to exclude areas where hard constraints were in place, normalized, and combined by means of a simple additive approach into a single "adoption index" for each adaptation, with each factor holding equal weight (detailed explanation in manuscript). For some of the identified spatial proxies, some pre-processing was undertaken as follows:

- Reduced tillage and conservation agriculture:
    - Processing aridity: following Prestele et al. (2018), cells with values representing sub-humid conditions were set to 0. Cell values were inverted.
    - Processing poverty: following Prestele et al. (2018), cell values in urban centers were set to 0 and subsequently replaced by the average value of neighboring cells (3x3 window). Cell values were inverted.
    - Processing soil-erosion: following Prestele et al. (2018), cells with exceptionally high values (> 95th percentile) were set to 1.
    - Some proxy datasets had slightly different extents and did not fully match the agricultural extent of Monfreda et al. (2008) or You et al. (2014). To ensure that the adoption factor proxies covered all agricultural production areas, we replaced any No Data pixels with the average values (or majority values for categorical factors) from a neighboring radius.

- Drip irrigation:
    - Processing aridity: following Prestele et al. (2018), cells with values representing sub-humid conditions were set to 0. Cell values were inverted.

- Processing poverty: following Prestele et al. (2018), cell values in urban centers were set to 0 and subsequently replaced by the average value of neighboring cells (3x3 window). Cell values were inverted.
- Processing soil: we included only soil variables in the database of Fischer et al. (2021) which showed "severe constraints" or lower for gravity irrigation and more suitable conditions for drip irrigation (only "moderate constraints" or higher). We selected values for the dominant soil only. For each soil variable, averages between sub-soil and topsoil values were taken, with sub-soil values weighted more heavily than topsoil based on average crop root length. Cell values were inverted where relevant so that highest values represented highest suitability. All soil variables were summed together in a single adoption factor, with each variable holding equal weight.
- Processing slope: we mapped share of slope between 0 and 10%. Cell values were inverted.
- Processing crop type: this layer was constructed based on hectares for fruit crops (identified as most suitable to drip) from the SPAM2010 dataset (temperate fruit crops, tropical fruit crops, other oil crops (International Food Policy Research Institute, 2019)), complemented by the MIRCA2000 dataset in areas beyond the SPAM2010 extent (Portmann et al., 2010)) (citrus, grapes, other perennial crops suited to drip irrigation).
- Processing land ownership: this step was based on ease of registering property at national level (steps, time and costs involved, DB05-15 methodology, 2005-2015 average) (World Bank, 2020), following the approach of (Piemontese et al., 2020).
- Some proxy datasets had slightly different extents and did not fully match the agricultural extent of Monfreda et al. (2008) or You et al. (2014). To ensure that the adoption factor

proxies covered all agricultural production areas, we replaced any No Data pixels with the average values (or majority values for categorical factors) from a neighboring radius.

- Variety change:
  - Processing poverty: following (Prestele et al., 2018), cell values in urban centers were set to 0 an subsequently replaced by the average value of neighboring cells (3x3 window). Cell values were inverted.
  - Some proxy datasets had slightly different extents and did not fully match the agricultural extent of Monfreda et al. (2008) or You et al. (2014). To ensure that the adoption factor proxies covered all agricultural production areas, we replaced any No Data pixels with the average values (or majority values for categorical factors) from a neighboring radius.

- Crop change:
  - Processing poverty: following (Prestele et al., 2018), cell values in urban centers were set to 0 an subsequently replaced by the average value of neighboring cells (3x3 window). Cell values were inverted.
  - Processing soil: we included the soil variables (from Fischer *et al*. (2008)) which Sys et al. (1993) report to influence crop-specific suitability. For crops not listed in Sys et al. (1993), we sourced soil suitability information from additional sources (Bodaghabadi et al., 2019; Everest, 2021; Kamali & Owji, 2016; Salah et al., 2001). We assumed that if no information on a soil attribute was listed in the literature for a particular crop, then that factor was not significant to defining its suitability. Soil texture classes were simplified to match the nomenclature of our soil variables data source (Fischer et al., 2008). We selected values for the dominant soil only. For each soil

variable, averages between sub-soil and topsoil values were taken, with sub-soil values weighted more heavily than topsoil based on average crop root length. Cell values were inverted where relevant so that highest values represented highest suitability. All soil variables were summed together in a single adoption factor, with each variable holding equal weight.

- Processing slope: we mapped the crop-specific slope thresholds reported in Sys et al. (1993) to determine crop suitability. For each pixel we identified the majority slope range and assigned it to the cell. Cell values were inverted.
- Some proxy datasets had slightly different extents and did not fully match the agricultural extent of Monfreda et al. (2008) or You et al. (2014). To ensure that the adoption factor proxies covered all agricultural production areas, we replaced any No Data pixels with the average values (or majority values for categorical factors) from a neighbouring radius.

Unlike the other adaptations, potential suitability for <u>irrigation expansion</u> was mapped by means of a binomial logistic regression analysis, based on the similar regional analysis of Malek & Verburg (2017). In addition to their biophysical factors addressing soil resources, climate variables and potential natural vegetation, and their socio-economic factors addressing dimensions of population density, accessibility, and market influence, we added information on poverty, land tenure, farm size, crop type, irrigation water availability and protected area networks, resulting in a total of 26 explanatory factors. **Table D2** outlines the rationale behind the chosen factors and specifies the respective spatial proxies.

We performed a forward conditional binomial logistic regression on 6 random balanced samples, with absence points situated within predominantly rainfed cropland areas (<=10% of area equipped for irrigation). Three samples included 9% of grid cells, and three additional samples included 18% of grid cells (respectively capturing >1850 and > 3700 points), each with a minimum distance of one pixel (10km) and following a check for multicollinearity (the Variance Inflation Factors did not suggest multicollinearity problems). Results for each regression sample are reported in **Table D3**. The regression results were evaluated by making use of the Receiver Operating Characteristic (ROC). All samples show high predictive results (Area Under Curve values > 0.8), and largely similar predictors. The results of the regression from Sample 4 were ultimately selected for constructing the adaptation index for irrigation expansion (**Table D4**) as they included the climatic predictors with greater (theoretical) significance to irrigation expansion (notably potential evapotranspiration and average temperature).

Prior to constructing the adoption index based on the regression results, some of the extents of the proxy datasets had to be modified where these did not fully match the rainfed agricultural extents of Monfreda et al. (2008) or You et al. (2014). This was done by replacing any No Data pixels with the average values (or majority values for categorical factors) from a neighbouring radius. The adoption index was limited to rainfed areas and areas where irrigation expansion would not compromise future ecological flows. This latter exclusion factor was based on the future irrigation expansion potential map of Rosa et al. (2020), including all expansion options (hard path, soft path, and soft and deficit path).

Table D2 – Adoption factors for irrigation expansion included as explanatory factors in the regression analysis and rationale for their inclusion.

Adoption factor	Rationale	Proxies and datasets (location factors)
Slope	Slope influences irrigated agriculture by altering workability of soil, fertility and accessibility of plots (Heistermann, 2006)	Share of slope between 0 and 10% (Fischer et al., 2008)
Altitude	Altitude is associated with different crop productions and climates which influence irrigation water requirements (Genius et al., 2014; Malek & Verburg, 2017)	Median elevation (Fischer et al., 2008)
Soil	Soil quality determines adoption of irrigation (Heistermann, 2006; Malek & Verburg, 2017; Piemontese et al., 2020)	% Sand content (Fischer et al., 2008)
		% Clay content (Fischer et al., 2008)
		Cation Exchange Capacity (Fischer et al., 2008)
		pH (Fischer et al., 2008)
		Soil carbon (Fischer et al., 2008)
		Reference soil depth (Fischer et al., 2008)
		Drainage (Fischer et al., 2008)
Climate	Arid environments have pushed development of irrigation (Malek & Verburg, 2017; Molle & Sanchis-Ibor, 2019; Neumann et al., 2011)	Annual precipitation (Fick & Hijmans, 2017)
		Average annual temperature (Fick & Hijmans, 2017)
		Solar radiation (Fick & Hijmans, 2017)
		Potential evapotranspiration (Zomer et al., 2008)
Potential natural vegetation	Degree of natural vegetation is likely to influence the potential distribution of irrigated agriculture (Malek & Verburg, 2017)	Potential natural vegetation (sparse trees, wild forest, remote forest and populated forest classes) (Ellis & Ramankutty, 2008)
Nature conservation	Limited potential for the expansion of irrigated agriculture within protected areas (Heistermann, 2006)	Protected area network (polygon data) (UNEP-WCMC, 2021)
Crop type	Crops have different water requirements and therefore different likelihoods to prompt the efficient implementation of irrigation (Heistermann, 2006)	Hectares under production of the most frequently irrigated crop classes in the region (i.e., sugar cane, rice, cotton, citrus, date palm, sugar beet, groundnuts / peanuts, maize, potatoes, other annual, other perennial) (Portmann et al., 2010)
Irrigation water	Water availability	River volume (Lehner & Grill, 2013),

availability	determines potential for further irrigation expansion (Heistermann, 2006; Neumann et al., 2011; Rosa et al., 2020)	sourced from (Linke et al., 2019) at: www.hydrosheds.org/page/hydroatlas
		Average groundwater table depth (Fan et al., 2013) , sourced from (Linke et al., 2019) at: www.hydrosheds.org/page/hydroatlas
Population density	Irrigated cropland is more likely to be situated in proximity to populated settlements, reducing costs through facilitated access to markets, infrastructure, etc. (Heistermann, 2006; Neumann et al., 2011)	Population density (CIESIN, 2015)
		Rural population density (CIESIN, 2011)
Poverty	Irrigation requires high costs (material and labor costs) (Neumann et al., 2011)	Share of people living in poverty (Elvidge et al., 2009)
Knowledge and material availability	Irrigated agriculture requires access to markets, specific materials and know-how (Neumann et al., 2011)	Market access index (Verburg et al., 2011)
		Market influence (Verburg et al., 2011)
		Density of roads (all types) (Meijer et al., 2018)
Farm size	Small farms are less likely to be able to justify investments in irrigation (Molle & Sanchis-Ibor, 2019)	Field size (Lesiv et al., 2019)
Land tenure	Tenant farmers are less likely to have access to subsidies or credit loan schemes, and are less inclined to invest in land they do not own (Alcon et al., 2019; Foltz, 2003; Jobbins et al., 2015; Oulmane et al., 2020; Pronti et al., 2020)	Ease of registering property at national level (steps, time and costs involved, DB05-15 methodology, 2005-2015 average) (World Bank, 2020), following approach of (Piemontese et al., 2020)

Table D3 – Results of the binary logistic regression tests for irrigation expansion run on the six different samples (*p<0.01).

	B (SE)					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Constant	*-1125.590 (252.401)*	*-815.317 (247.570)*	*-953.040 (254.225)*	*-1068.888 (176.524)*	*-877.528 (176.971)*	*-820.234 (177.089)*
Share of people living in poverty	-0.019 * (0.002)	-0.014 * (0.002)	-0.014 * (0.002)	-0.016 * (0.001)	-0.016 * (0.001)	-0.014 * (0.001)
Average groundwater table depth	-0.001 * (0.000376)	-0.002 * (0.000396)	-0.002 * (0.000397)	-0.001 * (0.000288)	-0.001 * (0.000295)	-0.001 (0.000288)
Hectares of frequently irrigated crop types	0.000028 * (0.000003)	0.000019 * (0.000003)	0.000019 * (0.000003)	0.000018 * (0.000002)	0.000020 * (0.000002)	0.000021 * (0.000002)
Soil drainage	-0.263 * (0.067)	-0.178 (0.066)	-0.193 (0.066)	-0.167 * (0.047)	-0.211 * (0.049)	-0.137 (0.047)
Slope	0.030 * (0.003)	0.026 * (0.003)	0.027 * (0.003)	0.025 * (0.002)	0.024 * (0.002)	0.028 * (0.002)
Degree of land ownership	0.020 * (0.005)	0.017 * (0.005)	0.019 * (0.005)	0.016 * (0.004)	0.012 (0.004)	0.018 * (0.003)
Field size	0.321 * (0.072)	0.232 (0.071)	0.271 * (0.073)	0.304 * (0.050)	0.249 * (0.050)	0.232 * (0.051)
Soil pH		0.000256 * (0.000066)	0.000188 (0.000066)	0.000213 * (0.000047)	0.000235 * (0.000049)	0.000337 * (0.000051)
River volume	0.000106 (0.000040)			0.000100 (0.000034)	0.000096 (0.000034)	0.000119 (0.000042)
Protected area		0.539 (0.177)	0.468 (0.179)		0.401 (0.129)	0.425 (0.127)
Median elevation		-0.001 * (0.000175)		-0.002 * (0.000211)	-0.002 * (0.000257)	-0.001 * (0.000121)
Potential evapotranspiration				0.003 * (0.000420)	0.001 (0.000441)	
Average annual temperature				-0.248 * (0.034)	-0.241 * (0.041)	
Solar radiation					0.000179 (0.000060)	
Annual precipitation						-0.001 (0.000232)
AUC	*0.827*	*0.823*	*0.824*	*0.824*	*0.830*	*0.821*

Table D4 – Results of the binary logistic regression utilized for mapping suitability for irrigation expansion (results from Sample 4, **Table D3**). The regression model was statistically significant, $X^2(1) = 1349.801$, $p < 0.01$, explaining 40% of the variance (Nagelkerke R^2) and correctly classifying 74% of cases. *p<0.01. ROC = 0.824.

	Sample 4	95% CI for Odds Ratio		
	B (SE)	Lower	Odds Ratio	Upper
Constant	*-1068.888 (176.524)*		0.000	
Share of people living in poverty	-0.016 * (0.001)	0.982	0.984	0.987
Average groundwater table depth	-0.001 * (0.000288)	0.998	0.999	0.999
Hectares of frequently irrigated crop types	0.000018 * (0.000002)0	1.000	1.000	1.000
Soil drainage	-0.167 * (0.047)	0.771	0.846	0.928
Slope	0.025 * (0.002)	1.022	1.026	1.029
Degree of land ownership	0.016 * (0.004)	1.009	1.016	1.023
Field size	0.304 * (0.050)	1.228	1.356	1.496
Soil pH	0.000213 * (0.000047)	1.000	1.000	1.000
River volume	0.000100 (0.000034)	1.000	1.000	1.000
Median elevation	-0.002 * (0.000211)	0.998	0.998	0.999
Potential evapotranspiration	0.003 * (0.000420)	1.002	1.003	1.004
Average annual temperature	-0.248 * (0.034)	0.729	0.780	0.834

- **The Ecocrop climate suitability model**

The Ecocrop model is a mechanistic model originally implemented in DIVA-GIS by Hijmans et al. (2001). It was developed to provide an assessment of climate change impacts on agricultural productions. The Ecocrop model determines crop-specific climatic suitability by assessing the extent to which monthly average minimum and mean temperature values, as well as total precipitation, exceed respective crop-specific thresholds outlining optimal, sub-optimal and unsuitable growing conditions. Aside from monthly climatic data, the model therefore requires information on the crop-specific growing period lengths (days) as well as the climate threshold values.

We reproduced the Ecocrop model in R (R Core Team, 2013). The suitability calculation is the following (from Ramirez-Villegas et al. (2013)):

- The model assumes each first day of the month may represent the beginning of a potential growing season, accounting for the fact that farmers may adjust sowing times to match more optimal growing periods. It therefore calculates suitability for 12 different growing seasons, each lasting the same indicated length of the crop growing period.
- Temperature suitability is then calculated by running **Equation D1** for each location and for each month of a growing period.

$$T_{SUITi} \begin{cases} 0 & T_{MIN-Pi} < T_{KILL-M} \\ 0 & T_{MEAN-Pi} < T_{MIN-C} \\ a_{T1} + m_{T1} * T_{MEAN-Pi} & T_{MIN-C} \leq T_{MEAN-Pi} < T_{OPMIN-C} \\ 100 & T_{OPMIN-C} \leq T_{MEAN-Pi} < T_{OPMAX-C} \\ a_{T2} + m_{T2} * T_{MEAN-Pi} & T_{OPMAX-C} \leq T_{MEAN-Pi} < T_{MAX-C} \\ 0 & T_{MEAN-Pi} \geq T_{MAX-C} \end{cases}$$

Where:

-T_{SUITi} represents the suitability index for the month *i*

$_{-MEAN-Pi}$ represents the mean monthly temperature at the given location *P* for the given month *i*

-$T_{MIN\text{-}Pi}$ represents the minimum average monthly temperature at the given location *P* for the given month *i*

-$T_{KILL\text{-}M}$, $T_{MIN\text{-}C}$, $T_{OPMIN\text{-}C}$, $T_{OPMAX\text{-}C}$ and $T_{MAX\text{-}C}$ represent the crop-specific threshold values. $T_{KILL\text{-}M}$ represents the crop's lowest "kill" temperature, + 4^{o}C (assuming that this value will therefore be reached at least on one day throughout the month). $T_{MIN\text{-}C}$ and $T_{MAX\text{-}C}$ represent the absolute temperature thresholds within which a crop can grow, while $T_{OPMIN\text{-}C}$ and $T_{OPMAX\text{-}C}$ determine the optimal growing conditions.

-a_{T1} and m_{T1} respectively represent the intercept and slope of the regression curve between $T_{MIN\text{-}C}$, 0 and $T_{OPMIN\text{-}C}$, 100, while a_{T2} and m_{T2} represent the intercept and slope of the regression curve between $T_{OPMAX\text{-}C}$, 100 and $T_{MAX\text{-}C}$, 0.

Equation D1 – Ecocrop calculation of a crop's temperature suitability to be run for each month during the crop's growing period (from Ramirez-Villegas et al. (2013))

- The growing period's suitability value is then set to equal the lowest value from any month within the growing season.
- The same suitability equation is applied to precipitation and the respective precipitation thresholds, with the only difference that the model assesses total precipitation throughout a growing period, rather than assessing monthly-specific averages, and without any "kill" precipitation threshold assessment.
- If suitability based on temperature or precipitation are to be assessed independently, then each respective suitability is established by selecting the growing period with the highest suitability value.
- If joint suitability based on precipitation and temperature is to be assessed, then the suitability values for temperature and precipitation are multiplied for each growing period. From the resulting 12 suitability values, the highest score is used to determine the overall

suitability, assuming farmers will adjust sowing dates to the most optimal period.

- We made use of the Ecocrop database's (FAO, 1994) default values on growing period length and climatic thresholds for all the crops, and did not undertake calibration or sensitivity analysis. The Ecocrop database was accessed via the DIVA-GIS software (Hijmans et al., 2001).

The Ecocrop model represents a simple approach to simulating crop climate suitability, and has known limitations, including:

- Variability in precipitation throughout the crop growing season is ignored, as well as the influence and impact of extreme events.
- The model does not consideration the possibility of multiple cropping cycles within a year.

Table D5 – Crop-specific temperature thresholds derived from the Ecocrop database (FAO, 1994). Values in brackets illustrate the threshold values explored under variety change.

Crop	Kill temperature (°C)	Minimum absolute temperature (°C)	Minimum optimal temperature (°C)	Maximum optimal temperature (°C)	Maximum absolute temperature (°C)
Common wheat (Triticum aestivum)	0	5	15	23 (25)	27 (30)
Durum wheat (Triticum durum)	0	6	17	25 (28)	30 (33)
Tomato (Lycopersicon esculentum)	0	7	20	27 (30)	35 (39)
Sunflower (Helianthus annuus)	-10	5	17	34 (37)	45 (50)
American upland cotton (Gossypium hirsutum)	0	15	22	36 (40)	42 (46)
European olive (Olea europaea)	0	5	20	34 (37)	40 (50)
European wine grape (Vitis vinifera)	0	10	18	30 (33)	38 (42)
Sweet orange (Citrus sinensis)	0	13	20	30 (33)	38 (42)
Mandarin (Citrus reticulata)	0	12	23	34 (37)	38 (42)
Pistachio (Pistacia vera)	*0*	*12*	*25*	*35*	*40*
Date (Phoenix dactylifera)	*-4*	*10*	*26*	*45*	*52*
Pearl millet (Pennisetum glaucum)	*2*	*12*	*25*	*35*	*40*

Table D6 – Crop-specific precipitation thresholds and length of growing cycle derived from the Ecocrop database (FAO, 1994). Values in brackets illustrate the threshold values explored under variety change.

Crop	Length of growing cycle (days)	Minimum absolute precipitation (mm)	Minimum optimal precipitation (mm)	Maximum optimal precipitation (mm)	Maximum absolute precipitation (mm)
Common wheat (Triticum aestivum)	170	300 (240)	750 (600)	900 (720)	1600
Durum wheat (Triticum durum)	150	400 (320)	500 (400)	700 (560)	800
Tomato (Lycopersicon esculentum)	110	400 (320)	600 (480)	1300 (1040)	1800
Sunflower (Helianthus annuus)	135	300 (240)	600 (480)	1000 (800)	1600
American upland cotton (Gossypium hirsutum)	175	450 (360)	750 (600)	1200 (960)	1500
European olive (Olea europaea)	255	200 (160)	400 (320)	700 (560)	1200
European wine grape (Vitis vinifera)	215	400 (320)	700 (560)	850 (680)	1200
Sweet orange (Citrus sinensis)	272	450 (360)	1200 (960)	2000 (1600)	2700
Mandarin (Citrus reticulata)	212	300 (240)	1200 (960)	1800 (1440)	4000
Pistachio (Pistacia vera)	*165*	*250*	*400*	*700*	*1100*
Date (Phoenix dactylifera)	*365*	*100*	*200*	*300*	*400*
Pearl millet (Pennisetum glaucum)	*90*	*200*	*400*	*900*	*1700*

- Adaptation potential index maps

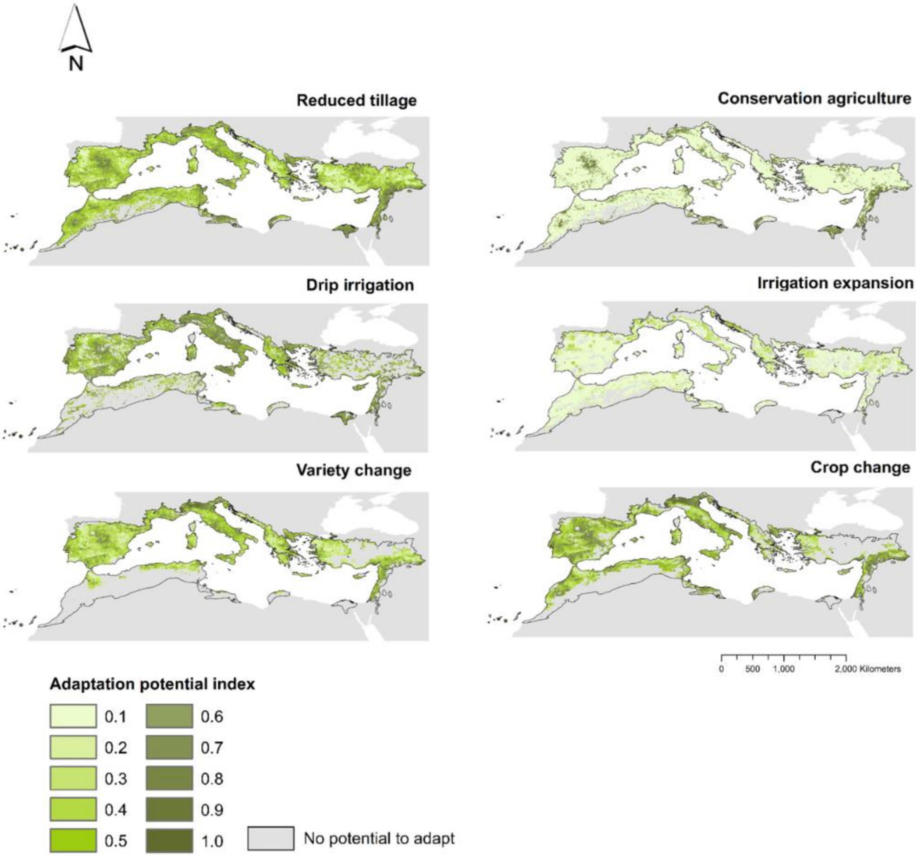

Figure D1 – Distribution of the adaptation potential indexes across the Mediterranean Basin. For variety change and crop change, mean adaptation potential index values from the crop-specific index maps are illustrated. The country boundary map was sourced from the Minnesota Population Center (2013), while the Mediterranean Basin boundary was sourced from Malek and Verburg (2019).

Note: throughout the manuscript results, values for wheat refer to averages from common wheat and durum wheat (unless otherwise specified).

- **Country-specific results**

Table D7 – Share of crop-specific harvested hectares within areas with the greatest potential for adverse climate change impact (%). Data reported for each national Mediterranean extent. Country boundaries were sourced from Portmann, Siebert and Döll (2010), while the Mediterranean extent was sourced from Malek and Verburg (2019).

	% Harvested hectares within areas with the greatest potential for adverse climate change impact								
Country	Wheat (common)	Wheat (durum)	Sunflower	Cotton	Tomato	Grape	Olive	Orange	Mandarin
Albania	11	4	0	14	19	18	19	19	N.A.
Algeria	19	22	15	9	7	53	10	21	24
Bosnia	56	1	0	N.A.	0	0	0	0	0
Croatia	42	21	N.A.	N.A.	0	0	0	0	0
Cyprus	0	30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Egypt	91	91	98	96	74	95	67	92	97
France	31	3	0	N.A.	0	0	0	0	0
Greece	81	81	87	87	80	72	73	80	80
Israel	79	59	79	0	71	38	2	0	0
Italy	40	20	0	N.A.	7	5	20	7	7
Jordan	1	1	N.A.	N.A.	2	1	27	1	1
Lebanon	0	0	0	0	8	0	0	0	0
Libya	3	4	N.A.	N.A.	0	0	15	0	0
Macedonia	0	0	0	0	0	0	0	0	N.A.
Malta	0	0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Montenegro	71	72	N.A.	N.A.	0	0	0	0	N.A.
Morocco	85	85	100	100	88	88	100	88	88
Palestine	0	0	0	N.A.	2	2	5	0	0

Portugal	28	46	45	N.A.	5	2	3	5	5
San Marino	N.A.	N.A.	N.A.	N.A.	0	0	0	0	0
Slovenia	49	49	0	N.A.	0	0	0	0	0
Spain	27	26	45	99	34	23	72	34	34
Syria	2	2	3	1	4	3	3	3	3
Tunisia	0	7	0	0	0	0	0	0	0
Turkey	65	66	88	41	71	71	71	71	71

Table D8 – Share of harvested hectares within areas with the greatest potential for adverse climate change impact and with tangible potential to implement adaptations (adaptation potential index values >0.1) (%). Data reported for each national Mediterranean extent. Country boundaries were sourced from Portmann, Siebert and Döll (2010), the Mediterranean extent was sourced from Malek and Verburg (2019).

Country	Share of potentially worst affected hectares with potential to adapt (assuming common wheat) (%)						Share of potentially worst affected hectares with potential to adapt (assuming durum wheat) (%)					
	Drip irrigation	Irrigation expansion	Reduced tillage	Conservation agriculture	Variety change	Crop change	Drip irrigation	Irrigation expansion	Reduced tillage	Conservation agriculture	Variety change	Crop change
Albania	15	35	88	1	37	46	15	36	87	1	47	61
Algeria	25	1	100	35	2	76	25	2	100	35	2	77
Bosnia	0	84	97	0	99	0	0	0	70	0	70	0
Croatia	0	83	95	1	37	6	0	91	98	2	99	0
Cyprus	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0	69	100	26	100	36
Egypt	73	0	100	84	0	5	73	0	100	84	0	5
France	46	24	99	5	74	1	46	23	100	7	100	0
Greece	30	25	84	14	21	54	30	25	84	14	20	55
Israel	47	0	100	78	5	66	47	0	100	80	0	47
Italy	30	18	87	10	54	73	30	20	87	9	50	77
Jordan	59	10	100	35	0	0	59	10	100	35	0	0
Lebanon	64	59	100	9	0	100	64	59	100	9	0	100
Libya	11	0	100	71	21	9	11	23	100	50	69	41
Macedonia	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Malta	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Montenegro	0	0	93	16	0	0	0	0	93	15	2	0
Morocco	29	4	97	20	5	67	29	4	97	20	5	68

Palestine	47	0	100	100	0	50	47	0	100	100	0	50
Portugal	13	5	48	2	12	82	13	5	49	3	21	83
San Marino	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Slovenia	0	55	97	4	0	0	0	55	97	4	4	0
Spain	36	5	95	22	14	74	36	5	95	22	14	75
Syria	26	0	98	49	42	83	26	0	98	49	42	83
Tunisia	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0	8	89	28	32	70
Turkey	15	16	83	10	13	24	15	16	83	10	13	25

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List of Publications

- **List of publications this thesis is based on**

Zagaria, C., Schulp, C. J. E., Malek, Ž., & Verburg, P. H. Potential for land and water management adaptations in Mediterranean croplands under climate change. *In Review.*

Zagaria, C., Schulp, C. J. E., Zavalloni, M., Viaggi, D., & Verburg, P. H. (2021). Modelling transformational adaptation to climate change among crop farming systems in Romagna, Italy. *Agricultural Systems*, *188*, 103024.

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- **Other peer-reviewed publications**

Wens, M., Johnson, J. M., **Zagaria, C.**, & Veldkamp, T. I. E. (2019). Integrating human behavior dynamics into drought risk assessment – A sociohydrologic, agent-based approach. *Wiley Interdisciplinary Reviews: Water*, e1345.

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Acknowledgements

There are many I owe my thanks to for supporting and enabling me to carry out this research.

A heartfelt thank you to my supervisors, Peter Verburg and Nynke Schulp, for the opportunity to work alongside you, for your insightful and careful feedback and guidance, for helping me grow as an independent researcher, and for your encouragement, availability, and patience. Nynke, thank you for your readiness whenever I've needed help along the way – I feel very fortunate to have been supported and accompanied by you throughout this Ph.D. journey, and am inspired by your commitment to a more caring and mindful academia.

Thank you to colleagues at the University of the Aegean, Thanasis Kizos and Dimitris Gounaridis, as well as Davide Viaggi and Matteo Zavalloni at the University of Bologna, for introducing me to the beautiful landscapes of Gera and Romagna, for facilitating our data collection process, and for valuable discussions and critical input. Thank you to Žiga Malek for your support and insight on the Mediterranean-wide analysis in Chapter 5, and for general help on all things EG, as well as for your encouragement and friendship.

This research was only possible because of the people in Lesvos and Romagna who took the time to share their stories, work, and opinions with our research team. Thank you for trusting and participating in this research process, for enriching our understanding of landscape stewardship, and for inspiring reflections on the meaning of place.

Many thanks to the members of my Ph.D. reading committee, Prof. Wouter Botzen, Prof. Felix Kienast, Prof. Ana Iglesias, Dr. Luuk Fleskens, and Dr. Anne van Loon, for taking the time to read through and challenge me on my work. I sincerely look forward to discussing and learning from you throughout the defense.

I am extremely grateful for all the connections and friendships made at the Environmental Geography Department through these many years. To my early office-mates Bianka, Koen, and Samantha – thank you for the fun working atmosphere, for welcoming me to the department, and for sharing valuable thoughts and reflections on research and academic life. Koen, thank you for your support in getting me acquainted with the HERCULES project and for being an entertaining companion on project excursions in Istanbul, Brussels, and Lesvos. To my longest 6th floor office-mate, Jonas – thank you for enthusiastically helping me brainstorm all sorts of research questions, for being a supportive listener whenever I've felt lost, and for the many after-work drinks, game nights, and travels. Katharina, I'm so glad we've met and so grateful for all of your sincere support and unique ability to brighten my days within and outside the VU. Thank you for being my paranymph and all the valuable help in getting me ready for this final step. Thank you Rosa for always checking in, for inspiring me with your determination, and for providing much-needed advice on defense preparations – I'm honored that you'll be standing by me as a paranymph when the day comes. Perrine, Claudia, Yue, and Liz, thank you for all the support and much-needed social breaks – I hope to continue learning and laughing with you inspiring ladies. Niels, thank you for many insightful discussions on research and sustainability, and for following through on multiple travel plans thought up at 1 A.M. in Café Chris.

A warm thank you also to all former EG colleagues including Harun, Bep, Leen, Christine, Emma, Brian, Franzi, Martina, Sarah, Astrid, Karina, Willem, Reinhard, Bagher, Mengmeng, Floris, Levi, and Anne Elise for sharing your exciting research, for helping me shape my own thoughts, and for a collection of treasured memories including the Ghent IALE conference, paranymph experiences, after-work book club dinners, trips to Texel, Slovenia, and the Ardennes, and more. My gratitude of course also goes to the current EG team: Rebecca, Vita, Kina, Jasper, Snow, Tim, Pierre, Thales, Michelle, Adna, Camille, Alex, Christian, Ciska, Rex, Tom, Job, Lanping, Saskia, Roos, Loes, Antonia and everyone else – thank you for exciting talks and brainstorms about research and our collective and individual futures, for offering help and advice in this last leg of the Ph.D., for evenings spent between Boele, fellowship screenings, and spontaneous bowling, and for making this such a special workplace. Thank you also to colleagues within the wider Institute for Environmental Studies. To Marthe and Toon for their support with agent-based modelling, to Nadia, Marleen, and Timothy for advice on navigating the curious world of Hora Finita, to Lena for involving me in Mediterranean research networks, to Marjolijn for all of your help and kindness, to the IVM Ph.D. Council for your important work, and to everyone for the many pleasant discussions and memories.

Thank you to Hannah, Loes, Harrie, Martina, Laurence, Sophia, Frankie, and the Bennecool family for years of friendship, for providing important support and taking me on adventures whenever I most needed a distraction from this work – I wish to visit all of you more often.

Thank you to my family for always being supportive and for welcoming me back to a loving home during holidays, wherever that may be. Thank you especially to my sister for advice and support on pretty much everything, for keeping me sane and somewhat healthy in the pandemic through 100+ days of zoom yoga, for introducing me to southern Mediterranean shores, and for being the most inspiring researcher. Ben, thank you for designing and putting together this original and beautiful thesis cover. Martin, thank you for being a careful observer of our natural world, for helping me see its wonders, for gently cushioning my falls, and for all of your patience and love.

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SENSE PhD Courses

- Research in context activity: 'Organization and facilitation of a stakeholder workshop validating and discussing an agent-based model's structure and results' (2016)
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Selection of Other PhD and Advanced MSc Courses

- Responsible Research and Innovation Interdisciplinary Training for Researchers, Athena Institute – VU Amsterdam (2016)
- Environmental Humanities workshops on ' Cultural landscapes', 'Waste', and 'Climate', Environmental Humanities Centre -VU Amsterdam (2016)
- Adoption of agricultural and conservation practices: insights from behavioural theory and the decision-making process, Wageningen School of Social Sciences (2017)
- Agent-based modelling for resilience, Wageningen School of Social Sciences (2017)
- In-depth workshop on agent-based model development, IVM-VU Amsterdam (2018)
- Research Integrity course, VU Amsterdam (2018)
- Start-to-teach day, VU Amsterdam (2021)

Management and Didactic Skills Training

- Writing entry for the HERCULES EU FP7 Project Cultural Landscapes Blog (2016)
- Co-organization and facilitation of half-day PhD workshop 'Reflection on personal research goals' (2016)
- Supervising three BSc/ MSc students with thesis (2021-2022)
- Teaching in the MSc course 'ERM Tools – Spatial analysis' (2016)

Oral Presentations

- *Simulating and discussing alternative landscape futures by means of agent-based models: insight from place-based explorations in the Mediterranean* . Ghent IALE-Europe Conference "From Pattern and Process to People and Action", 12-15 September 2017, Ghent, Belgium
- *Use and management of cultural landscapes of the future: insights from agent-based modelling*. HERCULES Final Conference & Consortium Assembly, 04-10 2016, Brussels, Belgium
- *Climate change adaptation and mitigation via targeted ecosystem service provision: developing a sustainable land management strategy for the Segura Catchment (SE Spain)*, SENSE-WIMEK Symposium – Hazard, Risk and Sustainability in the Soil Environment, 14 October 2015, Wageningen, Netherlands

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About the Author

Cecilia Zagaria was born in Rome, Italy, on May 9th 1991. She pursued her B.Sc. studies in Environmental Geography at the University of York (United Kindom) and received her M.Sc. in International Land and Water Management at Wageningen University (the Netherlands) with a specialization in Land Degradation and Development. As part of her M.Sc. training, Cecilia investigated the impacts of land use and management change on ecosystem services in Spain and Scotland, drawing on insights from spatial modelling and stakeholder interviews.

In 2015, Cecilia joined the Environmental Geography Deparment of the Institute for Environmental Studies at Vrije Universiteit Amsterdam first as a Junior Researcher, and soon after as a Ph.D. Candidate. Her doctoral research, presented in this thesis, involved the spatial exploration of adaptation processes in Mediterranean agricultural landscapes, and was undertaken in collaboration with researchers at the University of the Aegean (Greece) and the University of Bologna (Italy).

Today, Cecilia continues her employment in the Environmental Geography Department as a postdoctoral researcher contributing to the FutureWeb project. In this new role, her work is focused on evaluating new land use scenarios for Europe for 2050, scoping how the European Union's Green Deal may drive future land use change and effective ecosystem service provisioning in the region.