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ORIGINAL ARTICLE

An agent-based model of groundwater over-exploitation in the Upper Guadiana, Spain

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Abstract Irrigated agriculture is a main user of groundwater. Achieving a sustainable use of groundwater will often require agricultural land-use changes such as shifting to entirely different kinds of crops and/or technologies. Enhanced understanding of land-use change is hence required for developing policies for a sustainable water future. We use an agent-based model to investigate the history of irrigated agriculture in the Upper Guadiana Basin, Spain, in order to learn about the influence of farmers' characteristics on land-use change and associated groundwater over-use. A shift from vineyards and cereals to horticultural crops would provide a possibility for higher income with less water use. Such a shift cannot be observed historically. The model results suggest that risk aversion and path dependency are insufficient to explain this observation, and the organisational set-up of farms limiting the maximum labour force needs to be considered as additional explanatory factor. Furthermore, it is shown that different types of farms existing in the UGB can be expected to exhibit distinct responses to drivers of land-use change such as agricultural policies. It is concluded that a sound understanding of the social system making use of a resource is required to solve problems of resource over-use. This article demonstrates that agent-based models can be useful tools to enhance such an understanding even in situations of scarce and uncertain data that are often encountered when dealing with resource-use problems.

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Introduction

In many arid and semi-arid regions, aquifer over-exploitation causes water-quantity- and water-quality-related problems and a reduction in groundwater use is essential for achieving sustainability. Irrigated agriculture is the main user of groundwater in many parts of the world (World Water Assessment Programme 2009) and in some cases accounts for up to more than 80% of groundwater use (Llamas and Martínez-Santos 2005). Hence, in many regions, much of the required reduction in groundwater extractions has to be achieved in the agricultural sector. The amount of water needed for irrigated agriculture is strongly related to the irrigated area, to the water needs of crops planted, and to the irrigation technologies used. Achieving a sustainable use of groundwater will often require changes that go beyond improving efficiency of water use but imply land-use change such as shifting to entirely different kinds of crops and/or technologies with different practices, organisation of labour and distribution channels. Hence, an enhanced understanding of land-use change is required in order to develop policies for a sustainable water future.

The Mancha Occidental aquifer (MOA) in the Upper Guadiana Basin (UGB), Spain, is such a case of groundwater overexploitation. There, since the 1970s, the irrigated surface has increased and farming practices have changed towards water-intensive crops. The main drivers of this process have been advancements of pumping and irrigation technologies and policies favouring irrigated agriculture

(Llamas and Martínez-Santos 2005; Varela-Ortega 2007). This development has led to an over-exploitation of groundwater resources. In order to improve the situation, a change in land uses towards a reduced level of groundwater extractions is aspired (Confederación Hidrográfica del Guadiana 2008).

Changes in agricultural land use as those aspired for the UGB arise from a complex mix of influential factors from the economic, institutional,[1] technological, and socio-cultural domain (e.g. Edwards-Jones 2006; Rogers 1995; Garforth and Rehman 2005; see "Model description"), and similar drivers may invoke different responses in different regions (Napton et al. 2010). No general model allows prediction of land-use change in a specific region. In order to enhance understanding of the main characteristics of the system structure influencing prospective land-use changes in a specific case, one strategy is to learn from the history of this farming region.

In the study presented in this article, we investigate the history of irrigated agriculture in the MOA in order to learn about factors influencing land-use change and associated groundwater use in this region. Our point of departure is that farmers play a central role as they are taking irrigation decisions. They are influenced by high-level developments, especially (changing) policies and they are exposed to upcoming innovations which they might adopt to improve their business. But ultimately decisions on crops planted and technologies used are made at the farm level, and thus, farmers are key actors bringing about land-use change and associated changes in groundwater extractions. Understanding developments and decisions at the farm level is vital for taking influence on groundwater extractions. The case-specific literature provides information on driving forces (technological development and changes in regulations) and consequences (amount of irrigation) of the observed transition, but it leaves a gap in explaining how, e.g. a change in regulation leads to the corresponding observed consequences. We address this gap by focussing on the farmers which 'translate' context changes into changes in irrigated area and water use.

This study develops an agent-based model of agricultural land-use changes in the MOA. Following the above reasoning, the model's main focus resides at the farm level and it is used to explore the influences of farmers' characteristics on the dynamics of land-use change. Our model is designed as a thinking tool. We explore relations between (assumed) farmers' characteristics and overall model dynamics and compare the latter to longitudinal historical empirical data. Based on this, we draw conclusions on potential explanations for the empirically observed patterns and dynamics. Our approach does not pertain to a specific scientific discipline but instead integrates insights from various scientific fields in a way that addresses the main issues of our case-study region. Consequently, theory and concepts from various strands of literature but also case-specific knowledge and empirical data are used to select and specify conceptual building blocks of the model. Agent-based modelling is chosen as a methodology which is suitable to integrate insights from various relevant scientific fields and to incorporate various sources of information, e.g. case-specific data as well as qualitative general findings from the scientific literature.

The following first outlines the case of the Upper Guadiana Basin ("The Upper Guadiana Basin") and then describes and motivates the chosen methodological approach of developing a flexible, transparent agent-based model ("Methodological approach"). The model is described in "Model description" and "Simulation experiments" reports on simulation results. "Discussion" discusses the methodological approach and interprets simulation results, while "Conclusions" summarises the main findings.

The Upper Guadiana Basin

The Upper Guadiana Basin (UGB) is a rural area located in the Autonomous Region Castilla La Mancha in central Spain. Irrigation of farm land accounts for approximately 90% of total groundwater use while irrigation using surface water is hardly significant (Llamas and Martínez-Santos 2005). During the last decades, the amount of irrigated farming has increased and farming practices have changed towards water-intensive crops, especially in the Mancha Occidental aquifer (MOA), the area's main aquifer which accounts for 90% of the UGB's groundwater extractions (Acreman 2000). This development has led to an over-exploitation of groundwater resources in the MOA and endangered wetlands of high ecological value (Llamas and Martínez-Santos 2005; Martínez-Santos et al. 2008a, b). Although hydrological and climatic factors (e.g. droughts) are important to understand particular aspects of the problem, the decrease in groundwater level is strongly related to changes in agricultural land use. Changes in crops planted and in irrigation technology used determine the amount of water that is pumped from the aquifer and 'lost' due to evapotranspiration. A sustainable situation cannot be reached without significant changes in agricultural water use for irrigation (Bromley et al. 2001; Lopez Sanz 1999).

The development of irrigated area and water extractions shown in Fig. 1 can be ascribed to a combination of factors. Irrigation and pumping technology became widespread since the 1970s. Irrigated agriculture encompassed

[1] Here and in the following "institutions" refer to formal and informal rules.

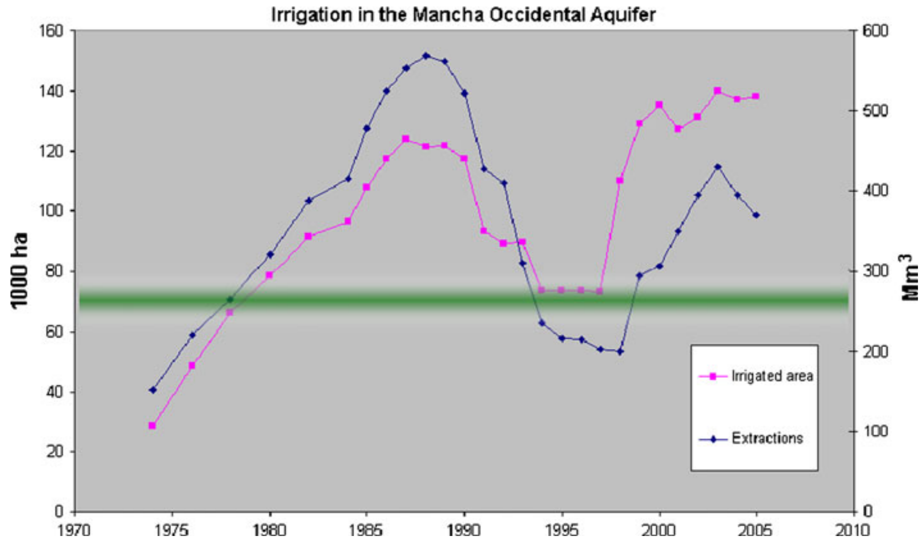


Fig. 1 Irrigated area and water extractions in the UGB's main aquifer. The shaded area represents estimated renewable water resources (sources: Llamas and Martínez-Santos 2005; Varela-Ortega 2007; Baldock et al. 2000)

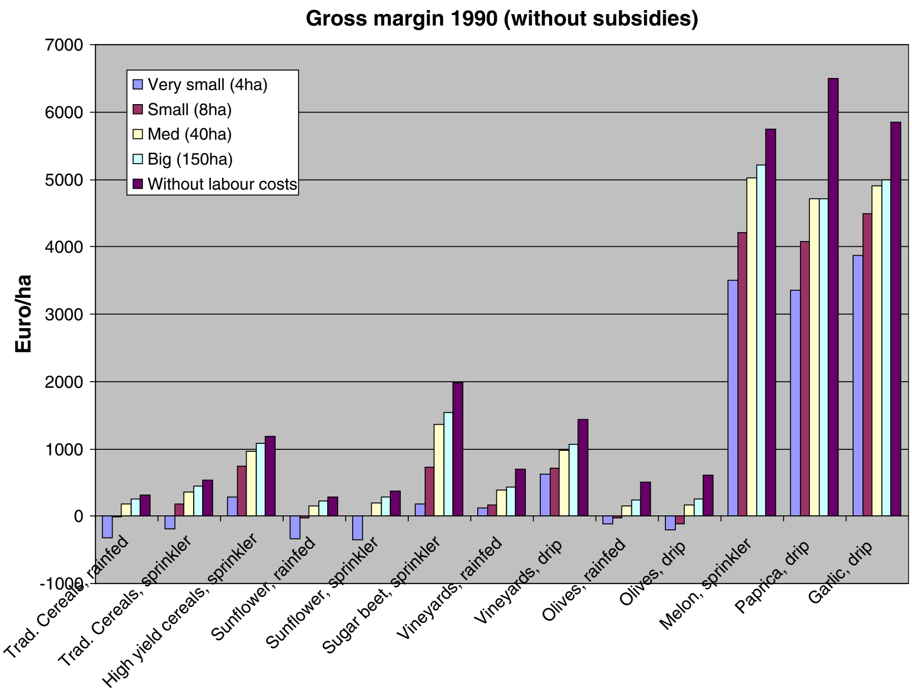
the possibility to plant water-intensive crops like maize, alfalfa and melons, which did not grow in the region before that time. It further provided the possibility to achieve higher yields of traditional crops like winter wheat and barley as well as of vineyards and olives.

All this led to a considerable expansion of irrigated agriculture in the UGB until the mid 1980s. To counteract the associated over-exploitation of groundwater resources, legal regulations and subsidy schemes were introduced.[2] In particular in 1985, the Spanish 'Water Act' passed water from being a private good to be a public one. Groundwater extraction rights for private use were granted based on the usage in 1985 but restricted to an upper limit. The Water Act further included the authorisation of river basin authorities to further limit allowed groundwater withdrawals in cases of aquifer over-exploitation. This regulation was implemented in the MOA in 1991, and legal extraction of groundwater was considerably limited. However, many farmers did not and still do not accept this regulation. They disagree with the obligatory pumping restrictions introduced in the MOA and take more water than granted (Ross and Martinez-Santos 2010; Llamas and Martínez-Santos 2005; WWF 2006). Aspirations to reduce groundwater extractions have also been hampered by the EU Common Agricultural Policy (CAP) which had considerable influence on the profitability of various kinds of crops, during some periods favouring water-intensive crops, especially maize (Varela-Ortega 2007). An agro-environmental programme (AEP) that compensated farmers for voluntarily reducing groundwater extractions was introduced in 1993, running in a first phase with some occasional modifications until 2003 and in a second phase with stronger modifications from 2003 on. The AEP was in its first phase more successful in temporarily reducing the irrigated area and groundwater extractions than the obligatory pumping restrictions. Still, the overall developments have lead to a non-sustainable situation (cf. Fig. 1). If the current level of extractions is maintained, wetlands cannot be recovered. Clearly, there is a tension between (short-term) socio-economic benefits from irrigation and avoiding potentially irreversible environmental damages. Various environmental groups have taken up the issue and have brought it to the political arena (Maestu 2005; Tàbara and Ilhan 2008). Current endeavours in the region aim at strategies reducing the environmental burden without constraining socio-economic prosperity too much (Confederación Hidrográfica del Guadiana 2008; Martínez-Santos et al. 2008b).

A change in land-use reducing groundwater extractions is aspired in the recently approved 'Special Plan for the Upper Guadiana' (SPUGB; Confederación Hidrográfica del Guadiana 2008) whose elaboration was decided in the National Hydrologic Plan of 2001. Concerning agricultural land use, the SPUGB intends inter alia to modernise irrigation technologies, to support so-called social crops providing much labour, especially horticultural crops, and to support innovative crops like energy crops. Aldaya and Llamas (2008) have argued that a paradigm shift in land use towards 'more cash and nature per drop' is needed and that an increase of high-value horticultural crops would provide a means to that end since they could provide more income on a smaller irrigated area while using less water. The gross margins of various crop types planted in the MOA are shown in Fig. 2. It is noteworthy that the predominant crops have been cereals (mostly winter cereals) and vineyards, although these crops are much less profitable than horticultural crops. Identifying reasons that have prevented a shift to more profitable crops in the past

[2] See "Appendix" for details of regulations.

Fig. 2 Gross margin of crops on different crop area sizes. Calculated from 1990 prices, yields, variable costs, labour costs, water pumping costs, without subsidies (data as used in this model, based on different sources; see Table 1 below and "Appendix")



decades is highly relevant in the context of future land-use change scenarios like those suggested by the SPUGB.

Methodological approach

Computer models provide the possibility to run simulations which produce dynamic patterns and time-series. As such they enable the study of linkages between a set of assumptions, in our case farmers' characteristics, and emergent properties of a system's dynamics like agricultural land-use change. The design of the model developed in this study shall be based on evidence of relevance for understanding the developments in the UGB. The modelling approach used in this study should hence facilitate the incorporation of insights from different scientific field and from various sources of information. Further, we aim at drawing conclusions about characteristics relevant in the case-study region from comparing overall model dynamics to longitudinal empirical data. For doing so, we need to tailor our methodological approach to the availability of empirical data.

Data availability

The UGB case is marked through scarce and uncertain historical data on land uses and water usage. A reason for this is that implementation of groundwater-based irrigation has been a 'silent revolution' (Llamas and Garrido 2007) driven by private initiative of farmers without much intervention, control or monitoring through the government until the mid 1980s. With the 1985 Water Act, Spain started to register water uses but more than 20 years later the registries are still incomplete (Hernández-Mora et al. 2007). According to Hernandez-Mora et al., the White Book on Water in Spain (MMA 2000) estimates that of the 500.000 operational wells existing in Spain, only 50% had been declared and less than 25% had been registered. Regarding the MOA, nearly 40,000 wells exist out of which only 17.000 are legally registered and also legal ones often do not have metering devices (Martínez-Santos et al. 2008a, b). Furthermore, the extent of the irrigated area is prone to uncertainties due to the existence of illegally irrigated areas. In an attempt to assess the total irrigated area in the UGB, the SPUGB reports on numbers[3] varying between 189.450 and 262. 868 ha (Confederación Hidrográfica del Guadiana 2008). This leads to high uncertainties regarding actual groundwater extractions. For example, according to Llamas and Martínez-Santos (2005), it is generally recognised that the all-time pumping maximum took place around 1988, but the estimations of this maximum vary between 570 and 650 Mm^3.

Historical data on the areas of different types of crops planted are scarce, too. According to the authors' knowledge, time-series on crop distribution are available only from 1990 onwards and only for the (much bigger) area of Castilla La Mancha. The cropping pattern in the MOA is expected to differ from these figures due to the especially

[3] Note that both numbers are considerably higher than the ones presented in Fig. 1 since that figure covers the MOA only and is based on official data likely underestimating the actual magnitude of pumping.

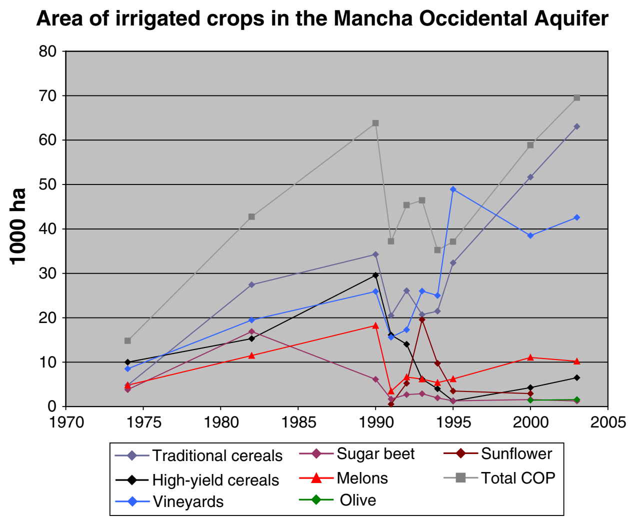


Fig. 3 Area of irrigated crops in the MOA (data taken from Llamas and Martínez-Santos 2005a, b)

good accessibility of groundwater and the associated intensity of irrigated agriculture as well as due to the prominent role of vineyards. Data on *irrigated* crops in the MOA are available (see Fig. 3), but given the uncertainty regarding illegal irrigation its exactness is doubtful. In sum, data are scarce and afflicted with uncertainties regarding water extractions, irrigated area and cropping patterns.

A flexible, transparent model

Limited data availability poses challenges for model specification (setting parameter values) and validation and must be considered in the modelling approach chosen. We follow the strategy to develop a flexible and transparent model. Transparency refers to the possibility to relate simulation results to model assumptions and parameter values. Through this, insights do not rest upon an uncertainly laden 'black box' model used to generate them. To achieve transparency, model complexity should remain modest.

The modelling approach should further be flexible in order to integrate insights from various relevant scientific fields (cf. "Model description") and to incorporate all available information from various sources, 'hard' data as well as qualitative information, general insights from the literature as well as case-specific information. It should further be flexible in the sense of providing the possibility of incorporating alternative assumptions, e.g. on actor rationality, in order to assess impacts of such assumptions.

Agent-based modelling

Agent-based modelling (ABM) is a suitable approach to incorporate various sources of information (Berger 2001) and offers a versatile approach to represent the richness of human behaviour and the interactions of humans and the environment. Agent-based models comprise self-contained software parts (the 'agents') which interact with each other and their (in silicio) environment (see Weiss 1999; Ferber 1999 and Heckbert et al. 2010 for introductions to agent-based modelling and Gilbert and Troitzsch 1999 for an introduction to simulation in the social sciences). Agent-based modelling allows using the full potential of a computer language to describe agents' characteristics, their perception of their environment, cognitive processes and agents' interactions. It is thus a very flexible method utilised in modelling exercises showing a remarkable bandwidth regarding scales (number of actors represented, spatial, temporal), levels of abstraction chosen, field of application, complexity of representation, etc. (e.g. Epstein and Axtell 1996; Holland 1996; Gilbert and Troitzsch 1999; Diamond 2002; Janssen and Ostrom 2006; Gurung et al. 2006; Happe et al. 2006). ABM of land-use change is a comparably young approach (cf. Parker et al. 2003; Matthews et al. 2007). Nevertheless, there has already been a progression from relatively abstract representations to applications to specific cases drawing on empirical data (Matthews et al. 2007).

Our model is used to explore the relations between (assumed) farmers' characteristics, resulting overall model dynamics and longitudinal empirical data, i.e. we aim at learning about the case-study region through a retrospective study. When doing so we do not aim at exact reproduction of empirical data sets (e.g. on groundwater extractions). Given the fact that data are afflicted with uncertainty in the magnitude as described above, the goodness of fit with empirical data is not necessarily meaningful anyway. Instead we aim at qualitatively reproducing patterns and trends in the empirical data which allows assessing in an explorative approach the influence of different factors on system dynamics.

Model description[4]

The case-related literature unisono mentions availability of pumping and irrigation technologies and policies (Water act, CAP, AEP) as major drivers of land-use change (Llamas and Martínez-Santos 2005; Varela-Ortega 2007). We use these insights as starting point and aim at enriching the picture through a representation of farm-related factors and processes.

The model developed models farmers as acting in a context comprising options and policies (see "The context:

[4] A complete detailed description of this model can be found at http://www.openabm.org.

options and formal rules"). The context is identical for all farmers, but the actions of a specific farmer within this context at a specific point of time depend on this farmer's characteristics ("Actors' characteristics influencing land-use change"), ongoing diffusion processes ("Diffusion of innovations") and the farm's history ("Path-dependency"). The model runs in steps of 1 year. Each year, each farmer chooses a land-use pattern as explained in "Actors' decision-making". Land-use change is considered as emergent outcome of options available, rules advising and penalising choices among options, of farmers' characteristics and of the development of land use itself. The development of crop patterns, the usage of irrigation technology and the amount of groundwater used are outcomes of model runs which can be compared with empirical developments.

The context: options and formal rules

Options are combinations of crops and irrigation technologies (e.g. 'rainfed vineyard' or 'drip irrigated paprika'). When utilised by a farmer, options are related to an associated area, forming a *land use* (e.g. 20 ha of irrigated vineyard). A set of such land uses then forms a farmer's *land-use pattern*. The land-use pattern is the unit that then is used to calculate outcomes (gross margin, water used, etc.). In this model, nine different types of crops and four types of irrigation (including not irrigating, i.e. rainfed cropping) are distinguished; resulting in a total amount of 23 options (not all combinations of crop and technology are feasible). Options are characterised by prices, yields, direct costs (fertilizer, seeds, etc.), and by the labour and water needed per ha.[5] Costs per labour unit and for pumping of water are also considered and assumed being the same for all options and actors. The attributes of options are based on those for crops (Table 1) and the efficiency of irrigation technologies (Table 2), i.e. the share of water pumped from the ground actually reaching the plant when using a specific technology. Further, options and land-use patterns are characterised by an associated risk. 'Risk' here refers to variability of gross margin due to short-term fluctuations of prices for products and inputs as well as variability of yields (due to weather conditions, pests, etc.). Some crops are inherently more risky than others. This was estimated based on empirical data on yields and prices for Spain in the period 1985-2005. Further, irrigation reduces risk since it decreases variability of yields. Diversification also reduces risk.

Formal rules provide constraints and incentives for using options. The rules implemented comprise the Water Act and associated pumping quotas, CAP prices for cereals and sunflower, CAP compensatory payments and the Agro-Environmental Programme (see "Appendix" for details of rule representation). Rules are changing over the simulated period of time according to historical developments. They have in principle two types of impacts: changing the profit of a land-use pattern through subsidies or penalties and rendering a land-use pattern legal or illegal, depending on the implicated amount of water used.

Actors' characteristics influencing land-use change

Change in agricultural land use in the MOA arises from farmers' adaptation to changing policies and from the adoption of innovations, especially pumping and irrigation technology. Research on farmers' decision-making and their adoption of policies and innovations forms a strand of literature in which economic approaches assuming the profit-maximising farmer for long have played an important role (Edwards-Jones 2006; Janssen and van Ittersum 2007). Since the 1990s, a considerable range of complementary factors has been identified in empirical studies, ranging from socio-demographics and the psychological make-up of the farmer, over characteristics of the farm household and the structure of the farm business to the wider social milieu (Edwards-Jones 2006). However, little is known about the relative contributions of these various factors in varying contexts and a general model is lacking. As Janssen and van Ittersum (2007, p. 629) state: '*Our understanding of farm decision making is still limited…*'. Nevertheless, what can be concluded from this strand of literature is that in Western developed countries, profit is indeed of major relevance for farmers' decision-making. But it can also be concluded that a model on land-use change should incorporate other objectives of farmers as well, which have to be identified with regard to the respective case.

Characteristics influencing gross margin

In this model, we consider that the *size* of a farm has a considerable influence on the profitability of certain types of crops, especially cereals can be produced more efficiently on larger farms since heavy machinery can be utilised which is not cost effective on smaller farms. The majority of farms in the MOA are small, having less than 20 ha. However, there are comparably few but very big farms (more than 100 ha) (Llamas and Martínez-Santos 2005). In this model, farms of five different sizes are considered to capture this diversity: *very small* (4 ha), *small* (8 ha), *medium1* (32 ha), *medium2* (70 ha) and *big*

[5] Labour needs per ha decrease with the size of area dedicated to a crop due to increasing efficiency. Table 1 illustrates this through showing labour needs for two different farm sizes for irrigated crops (only).

Table 1 Crop attributes (sources: Aldaya and Llamas 2008, Confederación Hidrográfica del Guadiana 2008; Piniés de la Cuesta 2006; Martínez-Santos 2007; MAPA 2008)

Categories	Price (1997) (€/100 kg)	Yield rainfed/ irrigated (100 kg/ha)	Water need irrigated (m^3/ha)	Variable costs rainfed/irrigated (€/ha)	Labour needed on land use of 3.5 ha/75 ha of irrigated crop (AWU[#]/ha)	Risk (rainfed/ irrigated)	Applicable irrigation technology*
Traditional cereals (wheat, barley)	14	21/42	2,800	130/180	0.08/0.015	0.24/0.19	R, F, S
Sunflower	20	8/18	3,000	70/260	0.08/0.015	0.27/0.29	R, F, S
High yield cereals (maize, alfalfa)	15	–/100	5,200	–/750	0.1/0.02	–/0.11	F, S
Sugar beet	5	–/770	6,050	–/1,500	0.2/0.06	–/0.17	F, S, D
Vineyards	18	50/100	2,350	200/250	0.12/0.045	0.32/0.16	R, F, D
Olives	36	17/24	2,050	100/150	0.09/0.045	0.32/0.35	R, F, D
Melon	27	–/260	4,550	–/1,000	0.25/0.07	–/0.18	F, D
Paprika	40	–/215	5,900	–/1,800	0.8/0.55	–/0.17	F, D
Garlic	100	–/74	5,130	–/1,300	0.22/0.1	–/0.14	F, D

[#] AWU means 'annual working unit' and refers to one person working full time

* *R* rainfed, *F* flood irrigation, *S* sprinkler, *D* drip

Table 2 Efficiency of irrigation technologies (source: Aldaya and Llamas 2008)

	Flood irrigation	Sprinkler	Drip
Efficiency	0.5	0.75	0.9

(150 ha). Farms are run with a certain amount of *family labour*. Family labour is considered available unpaid and is hence not included as costs in the calculation of gross margin.

Other objectives

As outlined above, farmers' decisions about land uses are made with several objectives in mind, though it is usually far from clear which are these objectives and what their respective influence on farmers' decisions is. We use case-specific knowledge to identify a set of potentially relevant objectives. García-Vila et al. (2008) provide results of recent semi-structured interviews of (southern) Spanish farmers. The by far most often mentioned reasons for cropping pattern decision-making were 'profitability & stability'. In this article, we thus introduce the possibility that farmers tend to avoid *risk* (accounting for the wish for 'stability'), which is also in line with the design of recent economic models addressing the situation in the UGB (Blanco et al. 2007; Varela-Ortega et al. 2006).

A case-specific additional aspect is that in the UGB many farmers take more groundwater than granted by formal rules. Thus, on the one hand, simply assuming that overexploitation can be avoided by imposing restrictions on water use and expecting all farmers always accept formal rules is misleading. On the other hand, many farmers do follow formal rules, although it would be profitable not to do so and the chance of being controlled and fined is very low in the UGB. In order to incorporate this situation, this model considers a *motivation to comply with formal rules*, which is independent of the risk of getting a penalty for non-compliance. The latter is incorporated in profit maximisation. Control of water laws is however very limited due to problems of monitoring and control (Llamas and Martínez-Santos 2005); thus, penalties play a minor role.

Another factor important for land-use changes in the UGB may be *labour intensity* of land uses. Changes towards more irrigated agriculture and especially suggested future changes towards horticultural crops imply higher labour loads for farms. However, family farms that are mostly run with family labour have some natural limit on labour capacity. In the UGB, big farms belong to land owners considering the land as capital investment, who are called 'office farmers' by small farmers (Llamas and Martínez-Santos 2005) and whose labour force is not restricted to family members. For those farmers, constraints on the applied labour force may however still arise from other sources like the availability of skilled workers or from the organisational structure of a farm. In our model, the labour intensity of a land use can influence the respective utility and we investigate the implications for land-use changes.

Box 1 Calculation of utility $U(p_i)$ of a land-use pattern p_i

$U(pi) = G(g(p_i))*R(r(p_i))*W(w(p_i))*L(l(p_i))$

G: function of the influence of gross margin $g(p_i)$

R: function of the influence of risk $r(p_i)$

W: function of the influence of labour (work) load $w(p_i)$

L: function of the influence of staying legal $l(p_i))$

$G(g) = g^{\gamma}$

$0 < \gamma \leq 1$ is a parameter representing decreasing marginal utility of gross margin (for $\gamma < 1$)

$$W(w) = Max\left[0, Min\left(1\left(1 - \frac{w-w_f}{\kappa-w_f}\right)^{\beta}\right)\right]$$

w is the amount of labour needed for a land-use pattern, κ sets an upper limit of the labour load that can be handled by a farmer f and w_f is the available family labour (it is $\kappa \geq w_f$). β determines the shape of W(w). It should be noted that if $w < w_f$ then $W(w) = 1$ and if $w > \kappa$ then $W(w) = 0$

$R(r) = (1 - r)^{\rho}$

The values of risk r associated with a land-use pattern as calculated in the model are in [0.0, 1.0]. ρ determines the shape of utility regarding r.

$L(l) = Max(l, 0.5^{\lambda})$

Being legal is binary: l ε {0 = illegal, 1 = legal}. If l = 1 (legal behaviour) L(l) = 1, thus utility is not reduced. If l = 0 (illegal behaviour), λ varies the impact of illegal behaviour on utility

In total the utility function is hence

$$U(p_i) = g^{\gamma} \cdot (1 - r)^{\rho} \cdot Max\left(0, Min\left(1, 1 - \frac{w-w_f}{\kappa-w_f}\right)^{\beta}\right) \cdot Max(l, 0.5^{\lambda}).$$

All farmers are assumed to have the same set of objectives, although those may be weighted differently by different farmers. Those objectives are having a high gross margin, having low risk, having low labour loads and staying legal. These multiple objectives are compared and related by a farmer when choosing among a set of considered land-use patterns.

Calculation of utility

The implementation of the decision-making of farmers rests on the assumption that farmers can invest time to think about this decision and thus, incorporate all objectives in their decision (instead of using a lexicographic heuristic considering only the most important objective). A utility function approach is chosen. The utility $U(p_i)$ of a land-use pattern p_i is calculated using a Cobb-Douglas type of function as described in Box 1. The respective parameters influencing the impact of the various objectives on utility may be set differently for different farmer groups (see "Simulation experiments").

Diffusion of innovations

A second strand of literature that appears to be of major relevance regarding land-use change relates to the diffusion of innovations. The literature on diffusion of innovations complements the above discussed works through focussing on the process of adoption in a population over time (in contrast to focussing on single farmers' decisions). It is empirically well established that the diffusion process (roughly) follows an S-shaped pattern: initially some 'innovators' adopt the innovation independently. While the innovation spreads and is increasingly recognised and accepted, the process speeds up and finally slows down again, when approaching a saturation level of adoption (e.g. Rogers 1995). There are many approaches to explain this diffusion pattern, ranging from mere economic approaches explaining diffusion through preferences and changing market situations to approaches from the social sciences highlighting the interpersonal communication and psychological dimensions of innovation diffusion. Elaborated models of innovation diffusion exist, e.g. including peer networks and heterogeneity of innovativeness[6] of potential adopters (e.g. Valente 1995). Such models have been incorporated in agent-based models of land-use change and innovation diffusion (Berger et al. 2007).

In the MOA, around 17,000 farms exist. We consider this number high enough to integrate an aggregate description of diffusion processes only, in order to reduce data needs and model complexity. An aggregated description also relieves this study from finding empirical evidence for and keeping track of changing network constellations and farmers' innovativeness (related to age,

[6] More innovative actors are more open to adopt innovations and thus in general earlier in doing so.

education) over the considerably long time period of 40 years. The Bass model is a diffusion model on an aggregated scale originating from the marketing sciences (Bass 1969; Mahajan et al. 1990). Although it reduces the complexity of a diffusion process to a minimum, it is found to perform well for forecasting purposes. The Bass model suggests external (e.g. advertisement) and internal (e.g. word of mouth) influence on non-adopters as driving forces for diffusion. The internal influence increases with the number of adopters, i.e. the diffusion of an innovation is modelled as a self-reinforcing process that tends towards a final saturation level of adopters. In this study, we adopt an implementation of the diffusion process similar to the Bass model; the more widespread an option is, the higher the probability that a farmer considers this option when pondering about future land uses (see step 1 in "Actors' decision-making").

Path dependency

Policy changes and diffusion processes affect farms having an individual history; thus, farmers' response to policies and innovations is contingent to the specific situation of a farm. In short, decision-making of single farms is path dependent. Path dependency means that current and future decisions are influenced by the history of this farm; for example, farmers have knowledge of planting certain crops but not on planting others and on using certain irrigation technology but not others. Adopting previously unused crops or technologies involves learning efforts and bears the risk of reduced yields during a period of learning. Furthermore, Balmann et al. (1996) have shown that path dependency can arise from the asynchronity of life cycles of assets, i.e. at each point in time some sunk costs exist which favour following the current path when making new investments (which then constitute sunk costs at a later stage and so on).

Regarding farmers in the UGB path dependency arises from a range of sources; for example, tree crops like vine and olives which are widespread in the UGB have life times of up to several decades and cutting them at an early stage means loss of capital. On the other hand, planting vineyards or olives includes up to 5 years without yield. Therefore, the area dedicated to tree crops can be expected to change only slowly, and decisions on planting or cutting trees are contingent to the age of trees and not easily reversed. Further, machinery and irrigation technology constitute investments that must be depreciated and constitute sunk costs (assuming that second-hand markets work on a suboptimal level). However, machinery and irrigation technology are not suitable for all types of crops, and therefore, previous investments limit the options of a farmer to change land-use patterns in the future (at least makes some options less attractive).

In this model, path dependency is considered in the following ways: farmers explore potential future land uses based on their current land-use patterns and not from scratch (see step 2 in "Actors' decision-making"). Further, individual farms build up stocks of irrigation technologies and accumulate knowledge on crops. The stock of irrigation technology of a farmer is represented on the one hand as area which this farmer can irrigate using a specific technology and on the other hand as available pumping capacity in m^3 of water (representing the number and capacity of wells owned by this farmer). This stock increases if a farmer chooses a land-use pattern whose area of a technology surmounts the respective current stock and/or whose water needs exceeds the current pumping capacity. The stock does not decrease. Farmers acquire knowledge by planting crops and using technologies. Knowledge is gained in an asymptotic learning process in which skills on planting a crop or using a technology increase in each year during which a crop or technology is part of a farmer's land-use pattern. Initially farmers have some skills regarding the crops they plant when the simulation is started, and additionally, all farmers have perfect skills on rainfed cropping and fallow land (set-aside). Farmers' decision among potential future land-use patterns depends (among other things) on the 'difference' of the respective land-use pattern related to his current situation in terms of stock of technology and knowledge. This 'difference' is a rough calculation of learning efforts and uncertainty with respect to innovations as well as investments necessary and sunk costs (see step 3 in "Actors' decision-making").

Actors' decision-making

The decision-making process integrating the model specifications developed so far comprises the following steps:

1. For each farmer *f*, a set of 'considered options' is identified whereas *f* considers those options that are combinations of crops and technologies both known to *f*. Further, unknown options are randomly considered, the probability increasing with usage of an option by other farmers, what induces a self-reinforcing diffusion process.
2. Based on *f*'s land-use pattern in the previous step p_0, a set[7] of 'considered patterns' p_i is developed. Each p_i is created through (randomly) iterating three basic operations on p_0 several times (the original p_0 is also considered further): (a) add one considered option which is not yet part of this pattern and associate some

[7] In the implementation used in this article for each farmer 1,000 "considered patterns" are developed in each time-step.

area to it, forming a new land use. The respective area is subtracted from a random other land use. (b) Remove one land use (if not the last), the respective area is added to a random other land use. (c) Re-scale two land uses: exchange some random area between two land uses.

3. Land-use patterns p_i that are too different from p_0 are discarded. 'Difference' is thereby evaluated based on two types of distances d between p_0 and p_i: (a) a distance d_s related to skills representing uncertainty and learning efforts associated with a change in the area of land-uses (especially implementation of new crops and technologies) and (b) distance d_c related to capital representing investments necessary and capital loss arising from the change in the area of land uses. Both distances depend on the history of this farm; hence, they capture the aspect of path-dependency on the farm level. For each land-use pattern p_i, f keeps p_i for further consideration randomly with a probability $p = (1 - d)^{\alpha}$. This random filtering is done for both types of distances, α_s (skills) and α_c (capital) being respective parameters that can be adjusted to explore the influence on model behaviour; that is, those patterns that are 'close' enough to f's current land use in both regards are likely kept for further consideration, while more distant p_i are likely discarded.
4. Consequences arising from formal rules (subsidies, penalties and legality) are evaluated for each of the remaining patterns.
5. The utility-maximising land-use pattern is selected (regarding this farmer's objectives and considering consequences from rules) as described above in "Calculation of utility".

Simulation experiments

In the experiments reported in the following, options and (changing) policies are the same for all model runs. To replicate the history of the introduction of irrigation, the model is initialized with farmers planting traditional crops. Following empirical insights, initially there is specialisation on vineyards or olives (mostly very small, small and medium1 farmers) as well as specialisation on cereals (mostly medium2 and big farmers). Some mixed farms of all sizes are also considered (having vineyards, olives and cereals) (see "Appendix" for specific information). Each run reported is an average of ten simulation runs with identical parameters but different random number sequences. In order to reduce computation time, simulations have been executed with 100 farmers per size class and aggregated results are extrapolated.[8] For the evaluation of the following simulations' results, we focus on the areas of irrigated crops since this constitutes the base for associated groundwater extractions. Figure 3 shows the available empirical data to provide a base for this analysis.

Exploration of effects of factors included in the model

The model facilitates exploration of assumptions of the importance of different factors through altering the parameters that determine their influence: α_s (skills), α_c (investments and sunk costs), κ, β (influence of work load), γ (gross margin), λ (staying legal), ρ (risk) (see "Model description" and Table 11 in the "Appendix"). In order to convey an understanding of the effects of those parameters, this section briefly reports on simulations in which each parameter alone is explored before the following sections report on more elaborate simulations.

The literature on farmers' behaviour (see "Actors' characteristics influencing land-use change") clearly identifies that profit is a major objective of farmers (in Western developed countries). This rather undoubted finding constitutes a baseline for all simulations: we assume $\gamma > 0$, i.e. increasing gross margin increases farmers' utility. When zero relevance is attached to all farmers' objectives except gross margin and no barriers to change between land-use patterns are assumed, then, as can be expected, this model generates a diffusion of those options which maximise gross margin until finally farmers only plant those crops. In accordance with Fig. 2, those options are drip irrigated garlic for smaller farms and drip irrigated melons for bigger farms. The diffusion process takes around 15 years. The results of this oversimplified model disagree very much with empirical data which show a dominance of cereals and vineyards (cf. Fig. 3).

All simulations reported in the following considering single influences besides gross margin reproduce a transition from rainfed to irrigated agriculture as observed in the MOA (cf. Table 11 in the "Appendix"). Indeed for a big part of the analysed parameter space, this model generates even stronger change than empirically observed, namely a strong change-over from vineyards and cereals to horticultural crops. The main driver behind the transition in the

[8] i.e. having e.g. 8,000 very small farmers in the MOA, each of the 100 model farmers of size very small represents 80 real farmers (cf. Table 6 in the "Appendix") and consequently land-uses of these farmers are multiplied by 80 when computing aggregated model results like overall land-uses and water extractions. In contrast to this each of the big model farmers only represents 3 real farmers. 100 farmers per size class are considered an adequate compromise between limiting stochastic effects, computational effort and taking into account the different relevance of farms of different sizes for aggregated results.

simulations is the increase in gross margin possible through irrigation. This increase is considerably stronger if farmers also change to horticultural crops (simultaneously with or subsequent to introducing irrigation; cf. Fig. 2). An interesting question is what has prevented such a switch to horticultural crops in the real system. This is all the more interesting regarding future scenarios aiming at introducing larger shares of horticultural crops in the MOA.

According to simulation results, risk aversion (parameter ρ) is not sufficient to explain dominance of vineyards and cereals. The potential profit through planting horticultural crops provides (too) strong incentives and furthermore risk can be mitigated to a large extent through diversification. Very strong risk aversion must be assumed to 'enforce' dominance of cereals and vineyards via the risk parameter (which however leads to non-plausible behaviour on the microlevel, see Table 11 in the "Appendix").

Barriers due to limited skills and capital (α_c, α_s) slow down the changeover to horticultural crops but do not prevent it. In this model, barriers do not prevent farmers from starting out with small areas of horticultural crops, learning how to farm them and extending the land uses slowly, probably waiting for favourable conditions. Planting only small areas of a crop entails reduced economies of scale (for this and complementary crops); however, given the high gross margins of horticultural crops, overall gross margin still increases even when planting some small area of horticultural crops only.

Regarding restrictions on water use, the simulation results show that even in cases in which all farmers act legally, horticultural crops dominate and cereals vanish completely. On small farms, water is sufficient for horticultural crops if some part of the farm is left fallow or planted with rainfed crops (this is true only if farmers have irrigated already before 1985 so they could claim water rights). On big farms, planting a small area of horticultural crops complemented by larger areas of rainfed vineyards or olives makes a better strategy (regarding gross margin) than irrigated cereals.

Restrictions of labour capacity provide the only[9] explanation for the dominance of cereals on large farms. However, on small farms, planting horticultural crops is superior to vineyards, the empirically observed dominant crop on small farms.

We conclude from this exploration of single parameters that no single parameter of this model is able to explain the empirically observed dynamics, especially the persistence and dominance of cereals and vineyards.

[9] In this model with parameters set as described in Table 11 ("Appendix").

Farm types

In the next step, we explore parameter combinations. The parameter space is too vast and simulations take too long to undertake a full scan of the parameter space via a Monte-Carlo-Analysis.[10] Further, not all possible parameter combinations are also meaningful. A random search in parameter space as conducted by a Monte Carlo Analysis may produce misleading results. Instead, the exploration of the parameter space presented here is guided by case-specific empirical knowledge about the types of farmers prominent in the UGB. We identify three types of farmers based on Hill (1993), Llamas and Martínez-Santos (2005) and Eurostat (2011) data:

- Part-time farm: the farmer and his family do not make a living out of farming but have income mostly from an off-farm job. The farm is almost exclusively run with family labour input in the residual time.
- Family farm: the farmer and his family live from farm income. The farm is run mostly with family labour (family labour is more than 50% of total labour force).
- Business-oriented farm: the main goal of the farm business is to make profit. The farm is run mostly with non-family labour input.

We use these types to identify meaningful clusters of parameter values (see Table 9 in the "Appendix" for more information). We ran simulations for each type with all farmers of all sizes belonging to this type. The figures showing the respective results including some parameter variations for those parameters we are most uncertain about for the respective type are shown in the "Appendix".

Results show for business farms a considerable influence of the labour capacity κ. A limitation of κ of business-oriented farms leads to a dominance of cereals on big business farms, which is consistent with empirical findings. In contrast to that, in simulations in which κ is unlimited, horticultural crops dominate on farms of all sizes. A limitation of κ is in line with empirical findings. Hill (1993) found an average of (only) 2.26 AWU for Spanish non-family farms[11] using

[10] One simulation run takes around 15–30 min on a standard desktop PC. We tried a structured exploration of the parameter space using a high and a low value (related to values in Table 10) for each parameter shown in Table 11 (not including β but γ instead). In total this leads to $2^6 = 64$ scenarios. Each scenario was simulated five times, i.e. in total 320 runs. This exercise remained however mostly inconclusive and is thus not reported here. More extensive explorations of the parameter space are not feasible given limitations of time and computer resources.

[11] In Hill's work these are all farms for which family labour makes less than 50% of the total labour force, i.e. what we call part-time farms are not included in Hill's non-family farms but only our business-oriented farms.

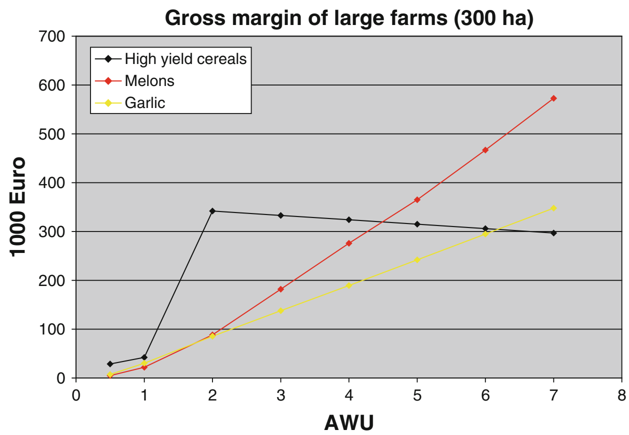


Fig. 4 Gross margin of large farms over labour input. Gross margin is calculated for the maximum crop area possible, considering limitations through the size of the farm and through the labour available (e.g. with 2 AWU high yield cereals can be planted on the whole 300 ha while melons and garlic can only be planted on ~17–18 ha). For sake of clarity the farm size is chosen to be 300 ha. Farms of this size are not represented in the model but do exist in the MOA. The effect of a local lock-in holds for smaller farms but is less pronounced

FADN[12] data. However, such an empirical observation does not explain why this is the case. A potential explanation is given in Fig. 4: regarding gross margin, cereals constitute a local optimum for low labour input on large farms. A considerable increase in labour input is required to actually increase gross margin through a shift to horticulture. In our model, there is no barrier that prevents an immediate increase of a farm's labour force from say 1 AWU to 4 AWU. In reality, this might constitute considerable organisational problems. A slow change-over to higher labour capacity may be prevented since it is (at first) not accompanied by increasing but rather decreasing gross margin.

The scenario for family farms shows a balance between irrigated cereals, vineyards and horticultural crops and an amount of irrigated area which is closer to empirical observations than the scenario for business-oriented farms. Cereals are planted mainly on big farms, vineyards and horticultural crops on smaller ones. Again, κ is of major relevance for this effect. Furthermore, it appears that only if the intrinsic motivation to comply with laws λ is very low, farmers irrigate vineyards (which is in line with empirical findings).

The scenario of part-time farms is outstanding regarding the persistence of rainfed crops, especially vineyards and olives, i.e. a limited overall amount of irrigation. A persistence of rainfed tree crops is in line with empirical findings (cf. "Appendix"). However, given the comparably small overall area of part-time farms (~14% of total area), part-time farming can be only a partial explanation for this empirical observation.

Combination of types

The analysis of farm types has shown that these different types and the according 'logics' of production generate quite distinct patterns of land-use change and may provide complementary partial explanations of the overall observed empirical situation. Hence, all the different types have to be considered. This section analyses results arising from simulations combining the three types and relating them to farm sizes as proposed in Table 6 in the "Appendix". Figure 5 shows the simulation's area of irrigated crops. Some more aggregated and some additional simulation results are presented as well, which we use in the following to discuss the model's performance in light of empirical findings (Figs. 1 and 3).

The COP[13] area rises until 1985 to a similar level as observed empirically (cf. Fig. 3). The subsequent drop in irrigated COP area after groundwater extractions have been legally limited is reproduced by the model, but underestimated. In the model, the drop results from big (and some medium2) farmers replacing irrigated traditional cereals through smaller areas of high-yield cereals. Instead of a shift to high-yield cereals, empirical data show a peak of irrigated sunflower around 1993, probably initiated through compensatory payments under the EU CAP which were introduced for sunflowers 1 year prior to cereals. The commonality between model results and empirical data is that irrigated traditional cereals are (temporarily) replaced by some other, more profitable COP crop. The model does not capture the empirically observable increase of irrigated COP area after 1995; instead, a higher level of horticultural crops is maintained. Horticultural crops also initially rise to a similar level in the model and empirically. However, empirically only melons play a role while in the model the main share is garlic. Data on melons and garlic shows similar gross margin and labour intensity with garlic being somewhat superior for smaller farms. The observed difference could be explained through small errors in data which artificially favour garlic over melons. A more significant shortcoming of the model is its inability to reproduce the empirical drop in the area of horticulture after 1990. Irrigated vineyards rise to an approximately similar level in the model and in empirical data, but an

[12] FADN is the EU Farm Accountancy Data Network, an instrument for evaluating the income of agricultural holdings and the impacts of the Common Agricultural Policy.

[13] COP is an abbreviation for cereals, oilseeds and proteins. In this model COP cover traditional cereals, high-yield cereals and sunflowers.

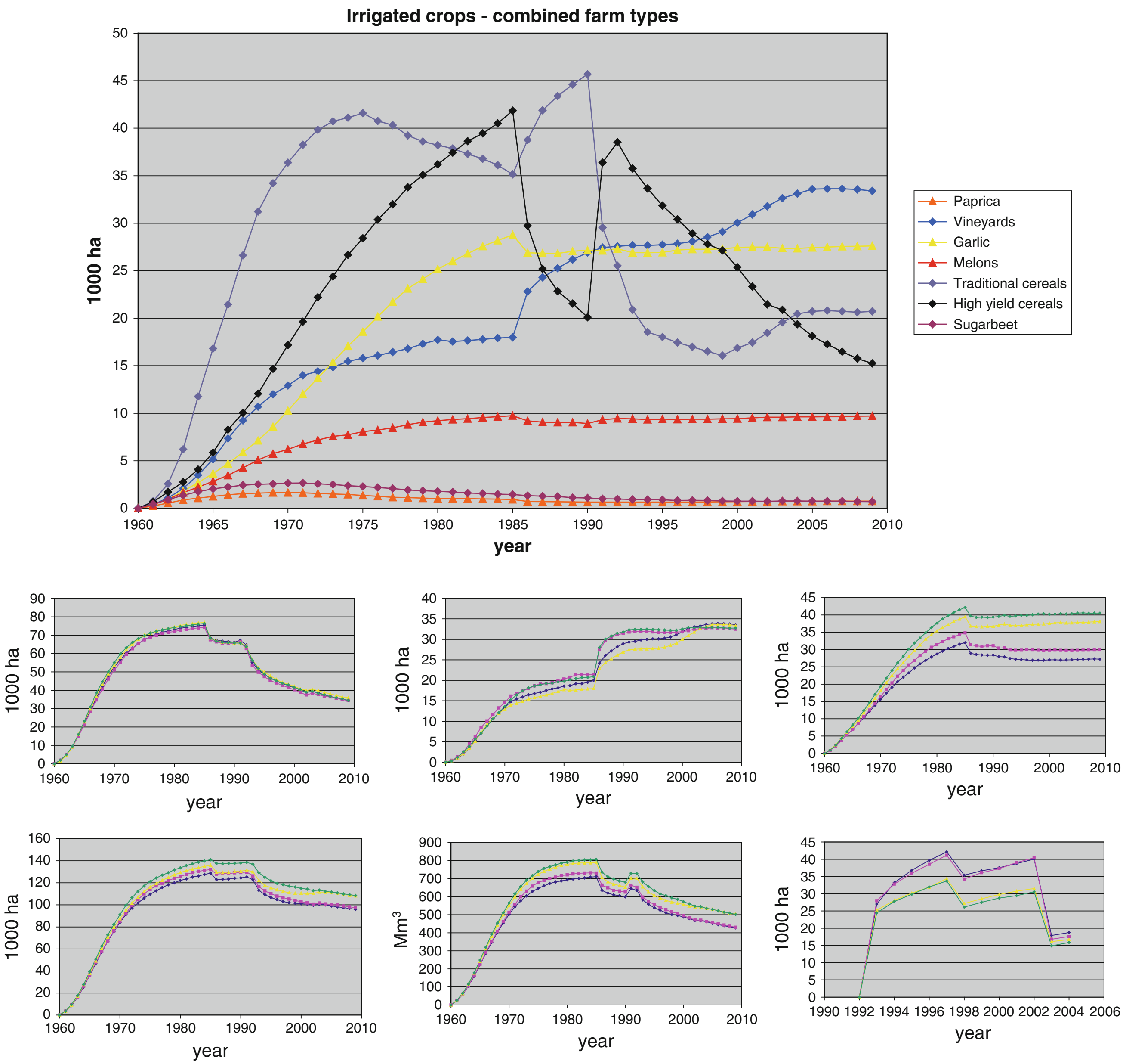


Fig. 5 The above figure shows irrigated crops for the scenario of combined farm types (parameter values as in Table 9). The small figures show (from left to right and top to down): irrigated COP area (COP = traditional cereals + high yield cereals + sunflower), irrigated vineyards, irrigated horticulture (melons + garlic + paprika), total irrigated area, water extractions, area under AEP. Parameter variations are $\kappa_{\text{business}} = 4.0$, $\kappa_{\text{family}} = 2.0$ (*blue*), $\kappa_{\text{business}} = 4.0$, $\kappa_{\text{family}} = 2.5$ (*pink*), $\kappa_{\text{business}} = 5.0$, $\kappa_{\text{family}} = 2.5$ (*green*) and $\kappa_{\text{business}} = 5.0$, $\kappa_{\text{family}} = 2.0$ (*yellow*) (colour figure online)

intermediate drop (in official data) of irrigated vineyards around 1990 is not captured by the model.

The total irrigated area and the water extractions resemble the development in areas of irrigated crops discussed above regarding COP and horticultural crops and also the shortcomings of the model to capture certain aspects of empirical data (cf. Fig. 1). The model captures the developments of irrigated area and water extractions before 1985 but does not reproduce a drop around 1985–1990 and a subsequent re-rise but simulation results instead show a slight decline. The area subscribed to the voluntary AEP may be an explanation for some of the observed differences. Empirical data shows a total area subscribed to the programme of around 80,000 ha in the time 1993–2002 and a strong drop in 2003 (Llamas and Martínez-Santos 2005a, b). The drop can be explained from the facts that in the second phase of the AEP (2003 onwards), the baseline amount of legally extractable water was adapted to the obligatory pumping quotas prescribed by the River Basin Authority, and compensatory payments per ha were decreasing with farm size which reduced the incentive to continue participation in the programme, especially for big farms. The model captures the drop, but the total area of subscription to the programme before 2003 is underestimated ($\sim$30,000 to 40,000 ha). Since joining the AEP requires reductions in abstractions and of the irrigated area, this shortcoming may explain some of the above differences between model results and empirical data. However, it does not provide an explanation for the empirically observed drop of horticultural crops around 1990 (previous to the introduction of the AEP) which is not captured by the model.

Discussion

Methodological considerations

In this model, a farmer's choice of crops and technologies depends on his objectives and his farm's (static) characteristics, on the (externally changing) context in which the farmer acts but also on the endogenous dynamics of the history of the individual farm and the visibility of innovations in the farmer population. This approach allows exploring factors underlying land-use change in an unfolding simulated history and to compare this to the empirically observed dynamics of agricultural land use. The model is flexible and complex enough to integrate, using a formal method, a set of factors simultaneously. Model building thus facilitates accounting for potential interactions among factors included, which cannot easily be achieved with less formal methods (e.g. qualitative analysis). Nevertheless, the complexity of this model remains on a level that maintains transparency, i.e. simulation results can be traced back to underlying assumptions. This is considered important because it allows developing general lines of argument which are independent of the details of this model (see "Interpretation of results"). Such reasoning can then flow into a debate without the need to understand the details of this model or the pros and cons of (agent-based) modelling in general.

The development of a model structures the analysis, makes it more precise and in our case has helped to identify oversimplified explanations of empirically observed phenomena. Used in this way as a thinking tool, agent-based modelling enhances understanding of the mechanisms behind land-use change and provides insights that are potentially transferable from the studied case to future scenarios and to other regions facing similar problems.

This model is designed to explore the implications of a set of assumptions which are intractable without a simulation model due to the complexity of the topic. Selected simulations were performed including exploration of some parameter variations, guided through increasing understanding of the model behaviour. The parameter space of the model was explored step wise, starting with single parameters and proceeding over parameter sets (farm types) to combinations of parameter sets (combination of farm types). Simulation results are found to be sensitive to (some) changes in parameter values but not to stochastic effects, i.e. the sequence of random numbers. The latter is shown in Fig. 9 in the "Appendix". Therefore, this model is considered suitable for an approach of exploring influence of assumptions (parameter values) on model dynamics running few simulations per parameter set only and focussing on averaged results. This is important since due to limitations of time and computer resources, no vast sensitivity analysis was performed and no complete exploration of the parameter space could be done.

In the stepwise approach outlined, parameter sets of later steps were partly specified based on previously gained understanding. Hence, calibration and validation are not clearly separated, especially no validation using independent data sets could be done. Simulation results are compared with known empirical patterns manually and qualitatively, discussing findings in relation to empirical knowledge and in the context of changing boundary conditions (policies). This leaves room for subjectivity. A further more general issue regarding the modelling of complex systems is that many structurally different models may be able to reproduce specific behaviour of a complex system (e.g. Sterman 2000; Beven 2002). For these reasons, it cannot be claimed that this model's structure is necessarily valid in the sense of truly resembling the structure of the real system. Indeed, simulation results show some shortcomings of this model to capture empirical evidence. The model's modular structure facilitates exploration of different or additional assumptions in future work. It is especially suitable to study alternative assumptions on farmers' decision-making.[14]

Other potential explanations for this model's shortcomings relate to the overall design. This model focuses on the farm level and as such does not elaborate on the embedding of farms in the region through distribution channels, long-term contracts, the role of local markets, organisation of local labour markets, etc. Further, heterogeneity regarding soil types and groundwater availability

[14] A model version implementing satisfying as a decision-heuristic of farmers has recently been completed and will be reported in future publications.

are not considered, doing so probably overestimates the share of land that is useable to plant profitable crops.

Consequently, the following discussion of the results obtained in the experiments described above has to be considered as thought-provoking input into a debate and not as presenting unquestionable evidence.

Interpretation of results

A very simplistic implementation of merely profit-oriented farmers turns out to be very much detached from empirical observations: all farmers, independent of the size of their farm, start to plant the most profitable option (drip irrigated garlic resp. drip irrigated melons) on the full area of their farms. Subsidies for cereals are insignificant in comparison with much higher profitability of horticultural crops. This finding confirms general insights from the literature that such a representation of farmers' decision-making is over-simplistic. The model explores the effect of additional factors influencing farmers' decisions and how they increase the match between simulations results and empirical findings. Intuitively, barriers to change like sunk costs and missing skills may seem a reasonable explanation for the empirically observed sticking to vineyards and cereals despite much higher profitability of horticultural crops. Also in the literature, farmers' skills, prior investments and limited capital resources are found to explain slow changes of land uses observable in agricultural systems (cf. Balmann et al. 2006). However, our model suggests that such explanations do not hold over the long time span considered here. Farmers could start planting horticultural crops on small areas when conditions are favourable, e.g. when some trees reach the end of their life span or some machinery is fully depreciated and new investments have to be undertaken anyway. Farmers can learn how to deal with horticultural crops without taking very high risk (when starting on small areas) and increase the respective areas in accordance with increasing skills.

A drawback for planting horticultural crops could be seen in risk arising from strong price fluctuations compared with cereals whose price fluctuations are limited through the CAP. But according to this model, risk does also not provide a very good explanation. Risk can be mitigated through diversification (the model considers only three horticultural crops whereas in reality more varieties are available). Further, price fluctuations may be higher for horticultural crops, but given their overall high level of gross margin, gross margin achieved is expectantly higher for horticultural crops even in bad years compared with cereals. Finally, although not considered in the model, higher average gross margin achieved through planting horticultural crops would allow for savings that would balance good and bad years.

In this model, the factor κ, representing an upper limit to the work-load manageable on a farm, is rather influential and limitations of κ constitute a necessary (although not sufficient) condition for approximating empirical data with this model. Hence, κ deserves some special attention. Technically speaking, the importance of κ can be understood from the fact that κ on the one hand constitutes a strict upper limit reducing utility to zero if labour load exceeds κ and on the other hand it targets labour effort, the crop attribute which shows the strongest relative differences[15] between crops besides gross margin. Potential explanations for the existence of such an upper labour limit differ for the different farm types. Part-time farmers do not primarily aim at achieving high profits, but work on the farm is restricted to what is manageable in their leisure time. Regarding business farms, a restriction of labour capacity has been partly discussed in "Farm types". Limitations of labour capacity must not exist per se, but a similar effect may arise from a local optimum of gross margin with respect to labour input (Fig. 4). Another explanation could be the overall availability of (qualified) workers. However, in the UGB, historically, many people left the area to Madrid because they could not find labour which makes the latter explanation somewhat implausible. Regarding family farms, limitations of labour arise from farming being a life style rather than an enterprise only. A recent review of the literature on farmers' values, goals and objectives (Garforth and Rehman 2005) emphasises the importance of farmers' 'intrinsic orientation to work, valuing the way of life, independence and performance of work tasks above expressive, instrumental or social dimensions of their occupation.' (Garforth and Rehman 2005, p.19). This importance of intrinsic orientation, especially independence and being ones' own boss, is found to be the most important orientation for all farmers in this study; (even more highly valued by smaller farmers than by medium sized or big ones). We suggest that many aspects which farmers value about farm life, like independence, having control and working outdoors, are strongly dependent on the size of the enterprise in terms of people employed. The more people are employed on a farm, the more desktop work has to be done and the bigger the need for planning and supervision. It can thus be argued that farmers prefer low labour loads that allow them to actually be a hands-on farmer and to run the farm as a family farm instead of becoming business oriented and to become a planner and supervisor. Farming being a life-style rather than an enterprise only and especially farmers'

[15] The most labour intensive crop can be (depending on land-use size) up to more than five times as labour intensive as the least intensive one while e.g. water use for irrigated crops is at maximum around twice as high for the most compared to the least water-intensive irrigated crop.

affection to their land could also explain some of the main short comings of the model regarding the reproduction of empirical data, namely an overestimation of horticultural crops (model) at the expense of COPs (empirical data) after 1995. In the model, medium and big farmers' utility of planting some horticultural crops and leaving considerable areas as fallow land[16] is higher than planting COPs. Such a strategy of not working considerable parts of the farms area might however contradict farming as a life style.

The results of simulations can be summarised as that this model suggests that simple explanations disregarding farmers' heterogeneity and the relevance of multiple objectives and constraints are not sufficient to explain the observed land-use changes. Using this model as a thinking tool facilitated an enhanced understanding of the limitations of such simple explanations. Instead the model suggests that combinations of several factors result in various 'logics of production'. The model further suggests that those types feature distinct characteristics and hence, exhibit quite distinct responses to driving forces of land-use change (availability of technologies, policies). Overall, it can be concluded that it is important to derive an enhanced understanding of the different characteristics of farm types when aiming at influencing land-use changes. This model can only be a first step in that direction.

Conclusions

This article presented an agent-based model developed as a thinking tool to enhance understanding of the role of farmers' characteristics for land-use change. It was applied to the case of the Mancha Occidental aquifer in the Upper Guadiana Basin, Spain. Regarding the methodology applied, it can be concluded that developing an agent-based model of intermediate complexity proved to be an approach which is complex and flexible enough to incorporate quantitative as well as qualitative knowledge from various sources. This model incorporates general findings from the literature on farmer behaviour and the diffusion of innovations. Those were selected and specified using case-specific knowledge. The chosen level of complexity was however low enough to maintain transparency, i.e. simulation results could be traced back to underlying assumptions. Given the uncertainties regarding the structure of this model and regarding data, this is considered important because it allows developing general lines of argument which can flow into a debate. In sum, this agent-based model was found to be suitable to study influences and potential interactions of various farmers' characteristics regarding land-use change.

The main findings are that considering profit orientation and single additional factors (e.g. risk aversion or barriers to change arising from sunk costs and a lack of capital) seems insufficient to explain the empirically observed land-use changes. The interactions of these and further factors—including farmers' skills and respective learning processes and especially the organisational structure of a farm which implies an upper limit to the manageable labour force—have necessarily to be considered to reproduce inhibition of more substantial change than observed empirically. Furthermore, different types of farms exist in the UGB (part-time farms, family farms and business oriented farms) which can be expected to differ regarding (to a combination of) these factors. It was shown that they can be expected to exhibit distinct responses to changes in boundary conditions like availability of new technologies and changing policies. It is hence important to acknowledge differences between farmers and to derive an understanding of the different characteristics of farm types when aiming at influencing land-use changes. Although the specific findings are open to debate (see "Methodological considerations"), it can be concluded that incorporating an elaborated representation of human behaviour is crucial for understanding land-use change and that a sound understanding of the social system making use of a resource is required to solve problems of resource over-use. Key uncertainties lie in human behaviour. Consequently, in order to achieve a reduction of groundwater extractions as well as maintaining economic prosperity future policies for the UGB should be diverse, targeting different farm types based on an enhanced understanding of their respective characteristics.

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Appendix

Formal rules

CAP

The CAP module in the model incorporates (Piniés de la Cuesta 2006; European Commission, 1997; Council of the European Union, 1999):

1. Changes in prices for COP products (=cereals, oilseed, proteins), i.e. in the model prices for traditional cereals, high-yield cereals, sunflower. Prices for

[16] Leaving land fallow results from limited labour capacity and water rights.

Table 3 CAP prices for COP products

Prices (€/100 kg)	Up to 1985	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	2005 onw.
Traditional cereals	21	21	21	21	21	21	21	21	18.9	16.8	14	14	14	14	14	12.9	11.9	11.9	11.9	11.9	11.9
High-yield cereals	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	20.3	18	15	15	15	15	15	13.9	12.7	12.7	12.7	12.7	12.7
Sunflower	45	45	45	45	45	45	45	20	20	20	20	20	20	20	20	17.3	15.4	13.4	13.4	13.4	13.4

vegetables, olives, vines and sugar beet are either not (directly) influenced by the CAP or actual market prices are above intervention prices for the period considered (hence, no direct influence of intervention mechanism) (Table 3).

2. Compensatory payments: reduction in prices for products are compensated by area specific payments (starting in 1992), including a set-aside obligation. This is distinguished in two schemes:

(a) Simplified scheme: a farmer's COP area is less than 43.8 ha (specified as 92t of yield in the regulation, corresponding area calculated from regional factor). In this scheme, there is no set-aside obligation; compensatory payments are paid for all COP areas with the compensation rate of traditional (rainfed) crops. Max set-aside area is equal to COP area excluding set-aside, (i.e. at maximum half of total area may be set-aside).

(b) General scheme: yield corresponds to more than 92t (area > 43.8 ha). Then there is a set-aside obligation in percent of COP area. The exact percentage has been defined on a yearly basis and has hence changed over years. In the model, set-aside obligation is always 10% of COP area. Maximum set-aside area is equal to COP area excluding set-aside (i.e. at maximum half of total area may be set-aside). If these requirements are met, crop-specific compensatory payments are paid (Table 4).

Rule of 'eligible land': only for the area of land which was dedicated to annual crops in 1991 compensation may be claimed for. In this model, eligible land is saved in 1991 as total farm area minus area of tree crops.

Water Act/pumping quotas

The 1985 water act entitles groundwater rights based on previous use. Based on this, the pumping quotas then introduce a strict reduction on the water use allowed per hectare (Llamas and Martínez-Santos 2005; Varela-Ortega 2007a, b; Piniés de la Cuesta 2006; Rosell and Viladomiu 1997; Lopez-Gunn 2003). The actual water quotas have been adapted on a yearly basis but are simplified in the model focussing on the main changes as described in the following.

Farmers irrigated areas are memorised in 1985 (excluding vineyards, vineyard irrigation is forbidden at that time). From 1986 onwards, farmers are allowed to use a baseline quota of 4278m^3 of water per ha of entitled land which is irrigated (excluding vineyards).

From 1991 onwards, pumping quotas are introduced with water rights based on the baseline quota as follows: 100% for the first (up to) 5 ha, 50% for the next (up to) 5 ha, 35% for the next (up to) 20 ha and 25% for the rest of the land.

From 1997 onwards, vineyards may be irrigated but only a reduced amount of water is granted (the baseline quota for vineyards is 2,000 m^3/ha compared to 4,278 m^3/ha for other crops). In the model, water rights arising from a mix of areas of vineyards and other crops are computed as follows: the entitled area is 'filled' with non-vine land as much as possible (to take advantage of the higher quota) and then filled up with vine area. Based on the respective shares, a weighted quota is calculated and the corresponding water rights for the farm size are calculated as outlined above.

The water act imposes a fine of 7 cents/m^3 water abstracted illegally. However, it is nearly not controlled at all. In the model, there is an assumed efficiency of control of 1% (1% of violations of this law are detected and have to pay the fine). It is assumed that farmers include a rational calculation of this risk to pay a fine in their calculation of gross margin, i.e. a penalty is included in the gross margin:

$$\text{Penalty} = \text{Max}(0, (\text{water}_{\text{extracted}} - \text{water}_{\text{allowed}})) * 0.07\,\text{Euro/m}^3 * 0.01.$$

AEP

From 1993 onwards, farmers are offered direct payments in exchange for voluntarily cutting down water use. Farmers, who choose to adhere to the programme, receive payments in proportion to water savings related to initial entitlements

Table 4 CAP compensatory payments for COP products

€ per ha	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Trad. cereals rainfed	0	38	75	114	114	114	114	114	123	132	132	132	132	132
Trad cereals irrigated	0	75	151	228	228	228	228	228	247	265	265	265	265	265
High yield cereals	0	109	219	331	331	331	331	331	358	384	384	384	384	384
Sunflower	198	198	198	198	198	198	198	198	172	152	132	132	132	132
Set-aside	145	145	145	145	145	145	145	145	123	132	132	132	132	132

under the 1985 Water act (three options are available: 50, 70, and 100%). The AEP is modified in 2003. For this second phase, allowed water-use volumes and respective reductions are calculated based on the water volumes established annually under the pumping quotas (Llamas and Martínez-Santos 2005; Varela-Ortega 2007a, b; Piniés de la Cuesta 2006; Rosell and Viladomiu 1997). It should be noted that there is a period (1993–2002) in which the AEP may grant more water than the pumping quotas do. In this case, in the model, farmers who subscribe to the AEP are considered acting legally.

In this model, the land-use pattern of farmers is memorised in 1992. The potential AEP area is calculated as area of all crops excluding vineyards. This area is adapted: in 1998–2002, olives and vineyards are excluded, since 2003 nothing is excluded. The maximum water quotas are calculated based on this area for each farmer, according to the chosen level of reduction (50, 70 or 100%) with respect to a baseline amount of water which is 4,278 m^3 per ha for 1993–2002 and the respective pumping quota (including size specific reduction) from 2003 onwards. The 70% option is no longer available after 2003. Compensatory payments for the options and years are shown in Table 5. The modulation since 2003 means that each farmer gets the highest compensation for the first 40 ha, for next 40 ha (40–80 ha) less etc.

Each year for each considered land-use pattern each option is checked (including non-participation). The option with highest payment is chosen (i.e. farmers participate in AEP if their land-use pattern allows to get AEP payments).

Vine irrigation banishment

Before 1997, irrigation of vineyards was forbidden (Lopez-Gunn 2003). This rule renders all land-use patterns illegal which include irrigated vineyards (only applicable before 1997).

Model initialization

The model starts before irrigated crops were introduced in the study area. The initial model state thus comprises only rainfed crops, namely traditional cereals, vineyards, olives and fallow land.

The initial areas of crops in the study area are estimated based on empirical data as follows. As a basis, data for the 'comarca La Mancha' (in Ciudad Real) for 2001 is used (Confederación Hidrográfica del Guadiana 2006). The comarca La Mancha can be used as approximation for the Mancha Occidental Aquifer (Pedro Zorilla, personal communication). Data for the autonomous Region Castilla La Mancha (Eurostat 2011), available since 1990, were used to estimate trends for the period 1990–2001. Data for Spain (Eurostat 2011), available since 1965, were used to estimate trends for the period 1960–1990. It was assumed that horticulture coming up in later years was planted partly on

Table 5 Compensatory payments under AEP (Varela-Ortega 2007a, b)

Compensatory payments (€/ha)	1993 …	1997 …	2001 …	2003…2006
50%	156	164	179	1–40 ha → 209 40–80 ha → 125 >80 ha → 63
70%	258	271	296	(No longer available)
100%	360	379	414	1–40 ha → 518 40–80 ha → 311 >80 ha → 155

Table 6 Distribution of farms according to sizes, types and crops planted (at model initialisation in 1960)

		% of all farms	Part—time	Family farm	Business-oriented	% specialisation per farm size	% farms of this size (model)	Empirical estimates
Very small		Specialist COP	0	0	0	0.0	46.5	46.8
ha	4	Specialist vine	15	16.5	0	67.7		
nr	8,000	Specialist olives	10	5	0	32.3		
Area of type	32,000 ha	Mix	0	0	0	0.0		
	% of types of very small		53.8	46.2	0.0			
Small		Specialist COP	0	0	0	0.0	35	35.1
ha	8	Specialist vine	5	16	0	60.0		
nr	6,000	Specialist olives	7	0	0	20.0		
Area of type	48,000 ha	Mix	0	7	0	20.0		
	% of types of small		34.3	65.7	0.0			
Medium1		Specialist COP	0	0	0	0.0	12	11.7
ha	32	Specialist vine	0	8	2	83.3		
nr	2,000	Specialist olives	0	0	0	0.0		
Area of type	64,000 ha	Mix	0	2	0	16.7		
	% of types of medium1		0.0	83.3	16.7			
Medium2		Specialist COP	0	0	2	42.6	4.7	4.7
ha	70	Specialist vine	0	0	2	42.6		
nr	800	Specialist olives	0	0	0	0.0		
Area of type	56,000 ha	Mix	0	0.7	0	14.9		
	% of types of medium2		0.0	14.9	85.1			
Big		Specialist COP	0	0	1.5	83.3	1.8	1.8
ha	150	Specialist vine	0	0	0	0.0		
nr	300	Specialist olives	0	0	0	0.0		
Area of type	45,000 ha	Mix	0	0	0.3	16.7		
	% of types of big		0.0	0.0	100.0			
	Types % of total		37.0	55.2	7.8			

Classification of farm sizes and respective numbers of farms according to Llamas and Martínez-Santos 2005, Lopez-Gunn and Hernadez-Mora 2001). Empirical estimates for '% of farms of this size' computed from 'nr' of farms of this type and total number of farms

smaller farms which initially likely had vines and partly on previous cereal area and that sugar beet was planted on previous cereal area.

This leads to estimated areas of crops in 1960 (in % of total area of the MOA): cereals 20%, vineyards 45%, olives 10% and fallow 25%.

The percentages of the farm types 'business farms', 'family farms', 'part-time farms' proposed in Table 6 (see below) were derived as follows:

Part-time farms:

- 'Owner works mostly off-farm' in 28.5% of cases in Spain (Eurostat 2011).
- 'Work time of holder' is 0–25% in 51.7% of cases (in Spain) respectively 67.3% (in Ciudad Real) (Eurostat 2011).
- Assuming that share of 'owner works mostly off-farm' in the UGB relates to the number for Spain similarly as

Table 7 Operationalization of specializations (used in Table 6)

	Specialist vineyards	Specialist olives	Specialist COP	Mix
Vineyards	0.8			0.2
Olives		0.8		0.1
Traditional cereals			0.7	0.4
Fallow	0.2	0.2	0.3	0.3

Table 8 Initial crop distribution (arising from Tables 6 and 7)

	Model crop areas in % of total area	Empirical estimates
Vineyards	44.6	45
Olives	8.0	10
Cereals	23.4	20
Fallow	24.0	25

Table 9 Heterogeneity of farm types regarding decision-making

	Part—time	Family farm	Business oriented
Monetary profit	Diminishing marginal utility of gross margin Farming is mainly a 'hobby'; farmer not dependent on farm income ($\gamma < 1.0$)	Diminishing marginal utility of gross margin Most important to secure some income but high profit is less important since the farm household has no structural requirement for profit ($\gamma < 1.0$)	Linear influence of gross margin on utility Profit is aspired, the higher the profit the better ($\gamma = 1.0$)
Risk	Risk neutral Farmer not dependent on farm income (ρ low)	Risk averse General finding from the literature: farmers are risk averse (ρ high)	Risk averse General finding from the literature: farmers are risk averse (ρ high)
Respect water law/pumping quotas	Medium intrinsic motivation Do not consider rightful that groundwater was transferred to public ownership but are not dependent on farm income (λ medium)	Low intrinsic motivation Do not consider rightful that groundwater was transferred to public ownership; perceive it as their right to pump as they used to before 1985 (λ low)	Medium intrinsic motivation Politically active, need to maintain credibility (λ medium or high)
Family labour (in AWU)	0.4	1	0.4
Hiring of additional workers	Very limited To address peak times (e.g. harvest) only (κ very low)	Limited Up to amount of family labour (per definition used to differentiate types) (κ low)	Yes (κ high or very high)
Influence of sunk costs of human capital/learning efforts (skills)	High Low motivation to change business (α_s high)	High Farmers have a life-time of experience with 'their' crop and style of farming (α_s medium or high)	Low Possibility to hire different workers with different skills, if required (α_s low or medium)
Influence of sunk costs (machinery, technology, trees) and necessary investments (capital)	Low Investments small (small farm size) and off-farm income available but low motivation to invest (α_c low or medium)	High Bad access to loans (α_c high)	Low Good access to loans (α_c low or medium)

Table 10 Operationalization of farm types as used in Fig. 5 in the main text

	Family labour	γ	ρ	κ	λ	α_c	α_s
Business farm	0.4	1.0	5.0	5.0	3.0	20.0	20.0
Family farm	1.0	0.5	5.0	2.0	0.5	30.0	30.0
Part-time farm	0.4	0.5	2.0	0.6	3.0	20.0	50.0

'work time of holder', it follows part-time farmers are 28.5%*67.3%/51.7% = 37.1% of all farmers.

Business-oriented farms:

– We use the differentiation between family and non-family farms suggested by Hill (1993) (FWU > 0.5 AWU, i.e. including here Hill's 'intermediate farms' in family farms). Hill identifies for Spain (1989) 16.5% of farms which are non-family. However, the FADN data used covers only 48.9% of Spanish farms, excluding small ones which are likely not business-oriented farms. A first estimate of non-family farms (i.e. our business-oriented farms) would thus be 16.5%*48.9% = 8.1%.

Table 11 Parameters and their effect on simulation results (all simulations performed with $\gamma = 1$)

Param.	Description	Effect on simulations
ρ	Determines the impact of risk on utility. The higher ρ, the stronger risk decreases utility Risk refers to variability of gross margin due to short-term fluctuations of prices for products and inputs as well as variability of yields	The following simulations have been performed: ρ ε {0.25,0.5,1,2,3,5,10,15,25,50} $\rho = 0.25$ shows no difference to $\rho = 0$. ρ ε [0.5,10]: farmers plant crops with highest gross margin and use diversification among those to reduce risk. The bigger the farm, the higher the effect of ρ (e.g. big farmers add garlic as second crop for $\rho = 1.0$ and add paprika as third crop for $\rho \geq 2.0$, while small farmers add melons as second crop only for $\rho > 5.0$). An explanation for size dependent responses are economies of scale whose non-linear shapes imply stronger effects when partitioning smaller areas compared to bigger ones $\rho \geq 15$: farmers strongly diversify their crops (up to 5 different crops) including less profitable but less risky crops (cereals). Farmers adapt land uses to make use of subsidies to further reduce risk. Although effects on the macroscale seem plausible, behaviour of individual farms on the microlevel is erratic and counter-intuitive, e.g. a drop of more than 50% in gross margin is accepted to reduce risk less than 10%
λ	λ varies the impact of illegal behaviour on utility. The higher λ, the stronger utility is reduced This parameter models complementary motivations to cost considerations to stay on the legal side	The following simulations have been performed: λ ε {0.5,1,2,3,5} All simulations are similar to the simulation with λ = 0.0 until the introduction of the water law in 1985 (before that the only regulation is that vineyards may not be irrigated but in these simulations vineyards do not play a role anyway) λ ε [0.5,1]: farmers reduce land use and leave residual land fallow in order to comply with water law. But after further reduction of legal water (pumping quotas) all farmers except very small ones switch back to previous patterns (the pumping quotas do not comprise further reduction for very small farms). This switching back occurs because loss of gross margin when complying with pumping quotas would affect utility stronger than becoming illegal. Maintaining reduced water use according to the water law (but not complying with pumping quotas) does not make sense since being legal is binary $\lambda \geq 2$: farmers stay completely legal (with some exceptions in transitory adaptation phases, e.g. shortly after introduction of pumping quotas; for $\lambda = 2$ big farmers switch back to being illegal as described above). Medium1 and bigger farmers comply with pumping quotas through switching to mostly rainfed vineyards complemented by some melons. They join the AEP
κ	κ represents the maximum labour force to which this farm is extendable. Hence, κ also constitutes an upper limit for the labour load of land-use patterns	The following simulations have been performed: κ was increased from 1 to 9 in steps of 0.5; the related β is set to 1.0 (see below) Very small farmers are not affected at all. Small farmers are only affected for very low values of κ and only in the way that garlic area is somewhat reduced and complemented by fallow to reduce labour load. Bigger farms plant irrigated cereals but after cereal prices drop in the mid 1990s they stop irrigation but join the AEP (for low κ with rainfed cereals for somewhat higher κ with (small) areas of garlic (rest is fallow)). The shift in strategy from horticulture (+fallow) as observed without labour limit to the described strategy occurs for medium1 farms for $\kappa \leq 2.5$, for medium2 farms for $\kappa \leq 4.0$ and for big farms for $\kappa \leq 7.5$

Table 11 continued

Param.	Description	Effect on simulations
β	β determines how utility drops with labour load in the range between a farm's family labour (no negative impact) and κ (utility = 0)	The following simulations have been performed: β ε {0.5,0.75,1.0,1.5,2.0}; κ was set to 5.0 since for high κ the effect of β can be expected to be most pronounced β does not induce qualitatively new dynamics but produces results which are similar to reduced/increased κ; e.g. {$\kappa = 5$ $\beta = 2$} produces very similar results as {$\kappa = 4$, $\beta = 1$}. β is thus set to 1.0 in all following simulations
λ_s	λ_s determines how frequently 'distant' land-use patterns are discarded from further considerations. Higher λ_s lead to more frequent discarding λ_s relates to land-use patterns' 'distance' to a farmer in terms of this farmer's knowledge and prior experience (skills)	The following simulations have been performed: λ_s ε {1,2,3,5,10,15,20,25,30,50} λ_s ε [1, 10]: λ_s induces a delay in developments which is however clearly recognisable only for $\lambda_s \geq 5.0$. The attractor of the simulations is not changed but for $\lambda_s \geq 10$ diffusion of utility maximising land-use patterns is delayed until after the simulation ends. On the microlevel changes between crops usually proceed over some few years, starting with a small area of the new crop which is then further increased. The delay induced by λ_s has to be interpreted carefully since it is dependent on the number of patterns generated in step 2 of the decision process (see "Actors' decision-making"): the higher the number of patterns generated, the faster farmers 'find' land-use patterns which allow both, high utility and 'testing' new crops/technologies $\lambda_s \geq 15$: simulations reach a stable (macrolevel) mix of garlic, melons and paprika for the size classes very small, small and medium1. On the microlevel, individual farmers are however specialised on one crop only. The likely explanation is that switches between specialisations are (almost certainly) 'filtered away' as too distant but intermediate land-use pattern featuring more than one crop are not chosen due to low(er) utility. For farms of size medium2 and big the macrolevel shows ongoing increase in garlic and melon area and an intermediate phase of much paprika
λ_c	λ_c is similar to λ_s but relates to land-use patterns' 'distance' to a farmer's current land-use pattern in terms of sunk costs and necessary investments	The following simulations have been performed: λ_c ε {1,2,3,5,10,15,20,25,30,50} λ_c induces a delay in developments which is however clearly recognisable only for $\lambda_c \geq 10.0$. The higher λ_c, the more gradual shifts become on the microlevel (i.e. farmers increase/decrease some crop area over several years). The delay induced by λ_c has to be interpreted carefully (see λ_s) λ_c does not produce stable lock-ins to suboptimal options (as does λ_s) because it features a random factor which is most probably low sometime for the respective shift (hence, the shift is only delayed, not prevented). The higher the level of λ_c, the later individual runs converge because random differences arising in the initial 'exploration phase' are maintained longer

Initialization of farmers is as described below in Table 6 but without differentiating between farmer types (all farms are assumed to have 1 AWU of family labour and identical parameter values)

- The average AWU/holding in Ciudad Real is only 65.7% of Spanish average and there are considerably more farms with 'work time of holder <50%' in Ciudad Real than in Spain (factor = 1, 18; these are likely mostly part-time farmers but could also be business farmers who do not work the land themselves). On the contrary, the share of holdings with ≥50 ha (likely being business farms) is higher in Ciudad Real than in Spanish average, i.e. evidence on differences between Ciudad Real and Spanish average remains inconclusive.

Family farms: we take the difference between total farms and part-time + business oriented.

Table 6 relates the farm types to farm sizes and compares the model population to empirical estimates.

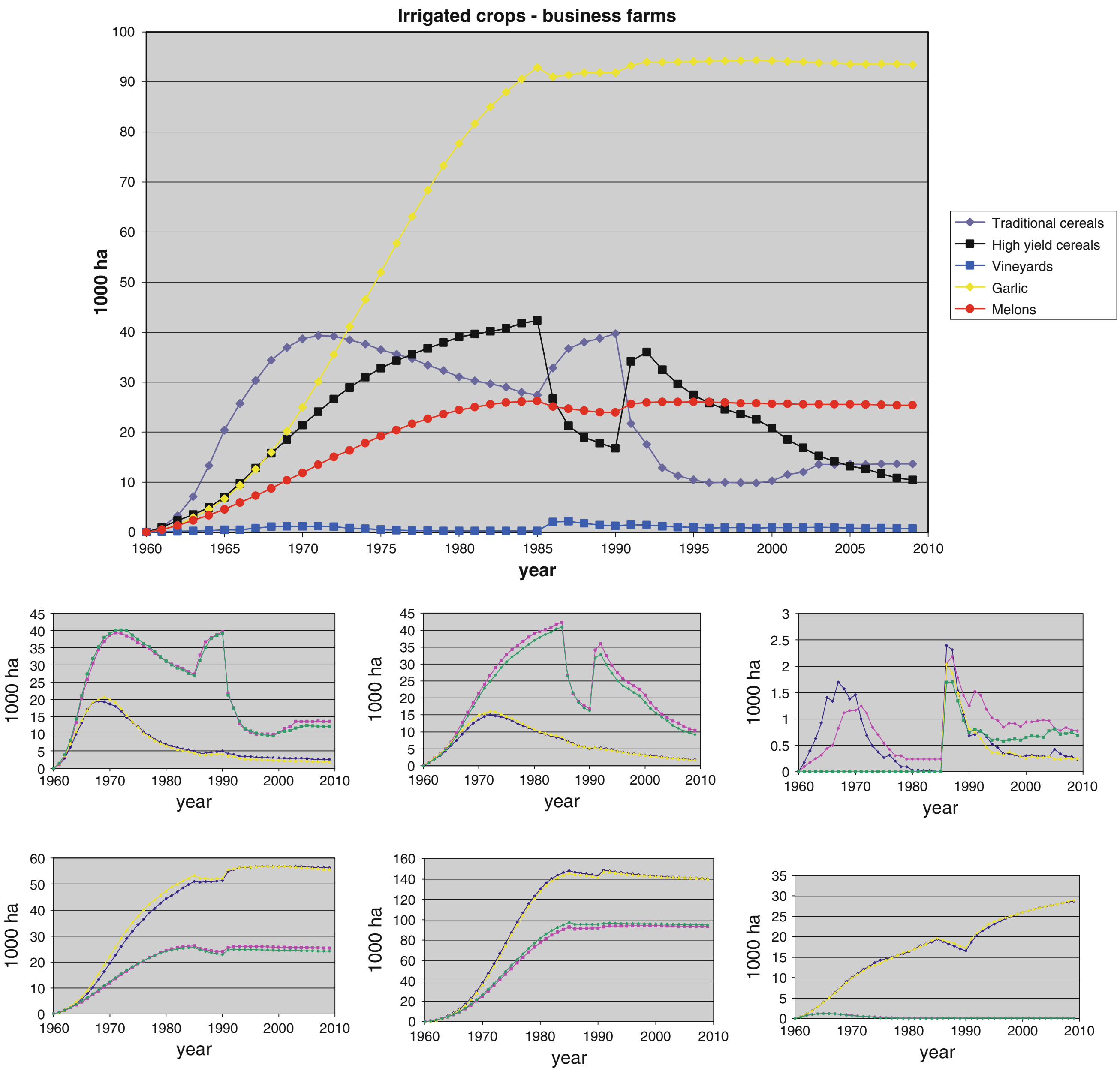

Fig. 6 Irrigated crops for the scenario of all farms being business-oriented farms. The above figure shows all crops whose area comprises visibly more than 0 ha for parameters $\gamma = 1.0$, $\rho = 5.0$, $\kappa = 5.0$, $\lambda = 3.0$, $\alpha_c = 20.0$, $\alpha_s = 20.0$. The small figures show single crops for parameter variations $\lambda = 3.0$, $\kappa = \infty$ (*blue*), $\lambda = 3.0$, $\kappa = 5.0$ (*pink*), $\lambda = 5.0$, $\kappa = 5.0$ (*green*) and $\lambda = 5.0$, $\kappa = \infty$ (*yellow*). Crops are (*from left to right* and *top to down*): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika (colour figure online)

Table 7 shows the operationalization of (initial) specializations of farmers and—based on Tables 6, 7 and 8 compares the initial model crop distribution to empirical estimates.

Relation between farm types and decision-making

Table 9 shows how the decision-making of the various types is assumed to differ and how this is translated into parameter values of this model (Table 10).

Additional simulation results

Table 11 shows the results of simulations in which one single additional parameter besides gross margin is analysed. Initialization of farmers is as described in Table 6 but without differentiating between farmer types (all farms are assumed to have 1 AWU of family labour and identical parameter values).

Figure 6, business-oriented farms (only), shows a considerable difference between $\kappa = 5$ and $\kappa = \infty$: for $\kappa = 5$

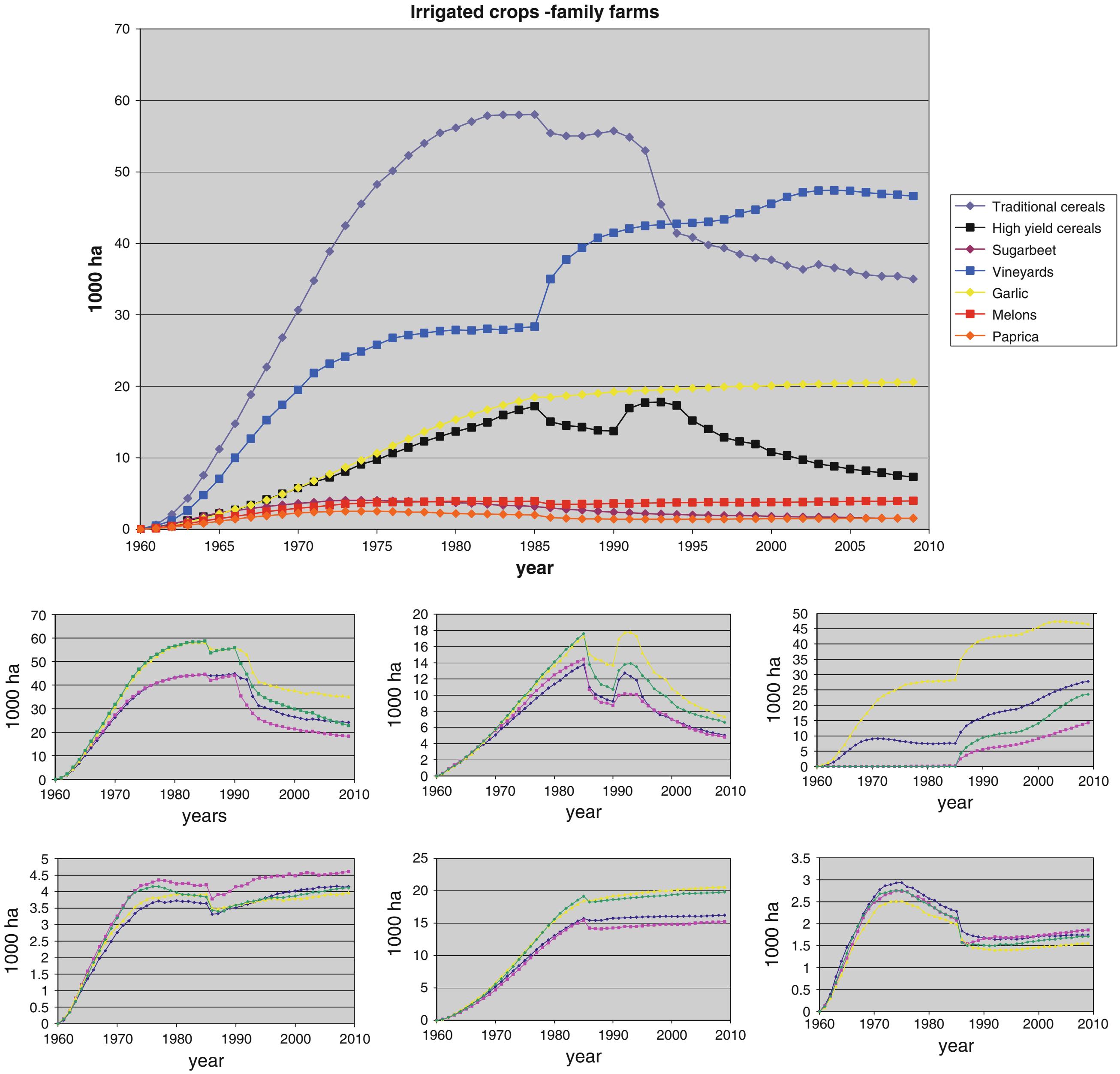

Fig. 7 Irrigated crops for the scenario of all farms being family farms. The above figure shows all irrigated crops whose area comprises visibly more than 0 ha for parameters $\gamma = 0.5$, $\rho = 5.0$, $\kappa = 2.0$, $\lambda = 0.5$, $\alpha_c = 30.0$, $\alpha_s = 30.0$. The small figures show single crops for parameter variations $\lambda = 0.5$, $\kappa = 1.5$ (*blue*), $\lambda = 3.0$, $\kappa = 1.5$ (*pink*), $\lambda = 3.0$, $\kappa = 2.0$ (*green*). $\lambda = 0.5$, $\kappa = 2.0$ (*yellow*). Crops are (*from left to right* and *top to down*): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika (colour figure online)

cereals play a somewhat stronger role while for $\kappa = \infty$ irrigated cereals are only a transient phenomenon and horticultural crops are the very dominant irrigated crops. An in-depth analysis of simulations with $\kappa = 5$ reveals that irrigated cereals are actually implemented on big and medium2 farms, which is in line with empirical findings.

The scenario for family farms (Fig. 7) shows a balance between irrigated cereals, vineyards and horticultural crops and an amount of irrigated area, which is closer to empirical observations than the scenario for business-oriented farms. Cereals are planted mainly on big farms, vineyards and horticultural crops on smaller ones. Again, κ is of major relevance for this effect. Furthermore, it appears that only if the intrinsic motivation to comply with laws λ is very low, farmers irrigate vineyards (which is in line with empirical findings).

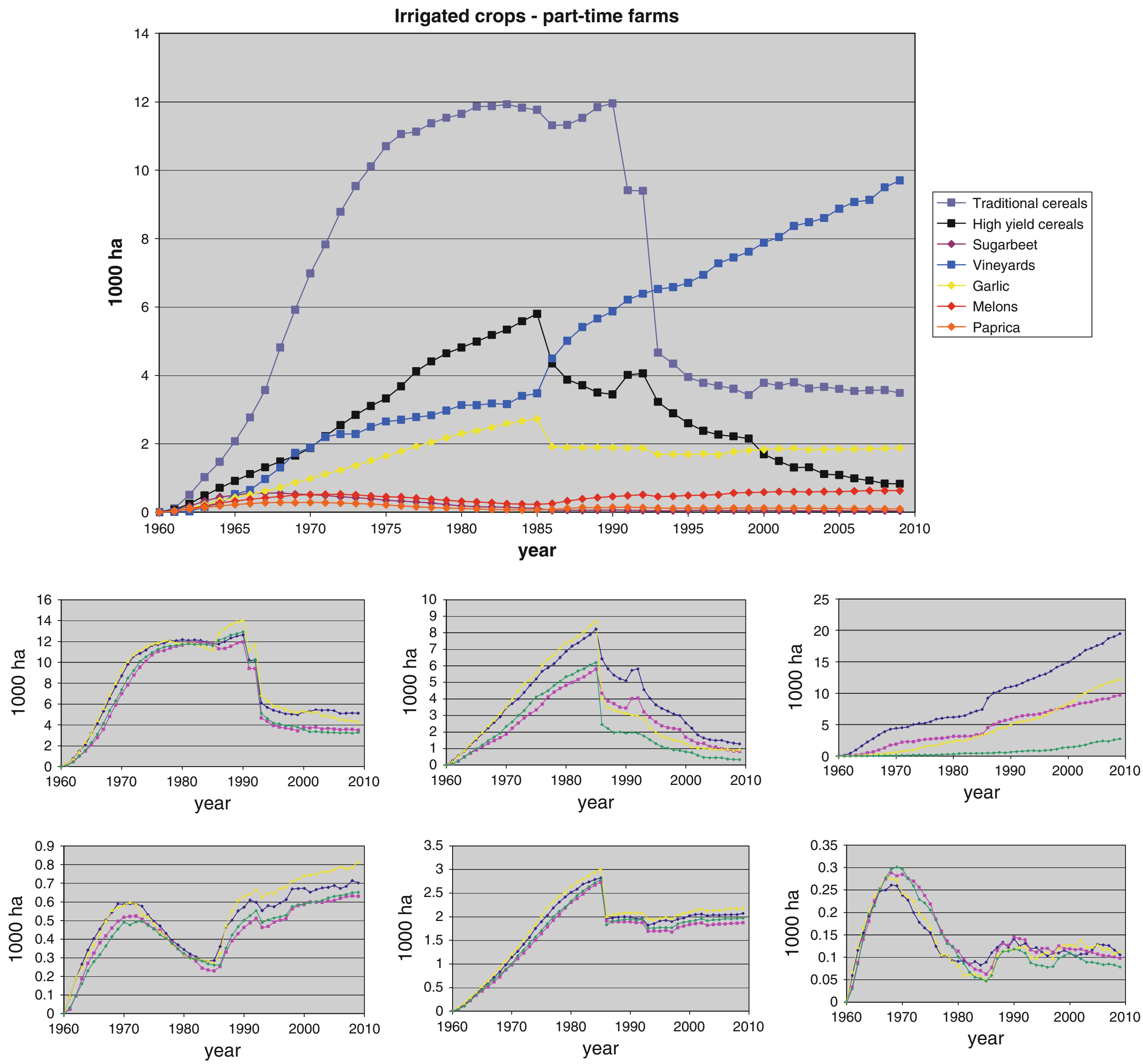

Fig. 8 Irrigated crops for the scenario of all farms being part-time farms. The above figure shows all irrigated crops whose area comprises visibly more than 0 ha for parameters $\gamma = 0.5$, $\rho = 2.0$, $\kappa = 0.6$, $\lambda = 0.5$, $\alpha_c = 20.0$, $\alpha_s = 50.0$. The small figures show single crops for parameter variations $\lambda = 0.5$, $\alpha_s = 20.0$ (*blue*), $\lambda = 0.5$, $\alpha_s = 50.0$ (*pink*), $\lambda = 3.0$, $\alpha_s = 50.0$ (*green*). $\lambda = 3.0$, $\alpha_s = 20.0$ (*yellow*). Crops are (*from left to right* and *top to down*): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika (colour figure online)

The most prominent feature of the part-time farm scenario (Fig. 8) is the low overall extent of irrigated area. This is not too astonishing considering that even big farms have only ~0.5 AWU available, which is too little to run bigger farms. Part-time farms of size medium1 or bigger are exceptional, if they exist at all in the MOA. It is hence reasonable to focus the analysis on smaller farms.

The model's sensitivity against random numbers is limited, what is shown in Fig. 9 which shows ten runs with identical parameter values but different random number sequences. The runs in Fig. 9 differ somewhat in quantitative terms, but all show similar qualitative dynamics. The influence of random numbers is not strong enough to induce path dependency on the macrolevel (as e.g. in the models of Arthur (1994)).

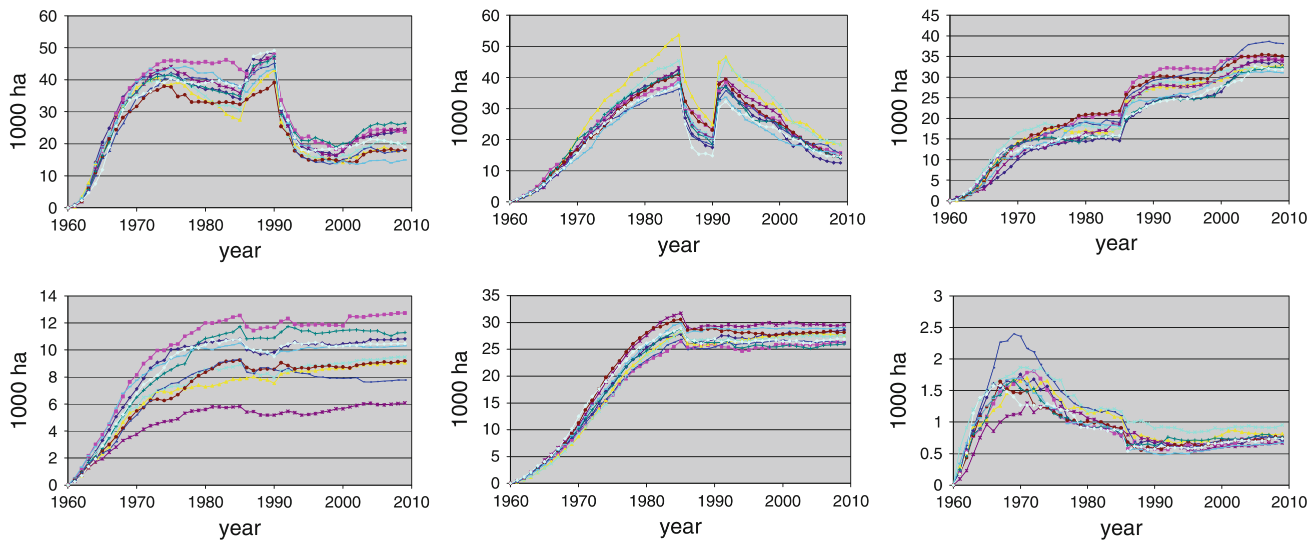

Fig. 9 Ten runs with identical parameters as in Table 10 but differing random number sequences. The figures show the areas of irrigated crops on the aggregated level (*from left to right* and *top to down*): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika

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