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Earth System Dynamics Discussions

How model paradigms affect our representation of future land-use change

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Abstract. Land use models operating at regional to global scales are almost exclusively based on the single paradigm of economic optimisation. Models based on different paradigms are known to produce very different results, but these are not always equivalent or attributable to particular assumptions. In this study, we compare two pan-European land use models that are based on the same integrated modelling framework and utilise the same climatic and socio-economic scenarios, but which adopt fundamentally different model paradigms. One of these is a constrained optimising economic-equilibrium model and the other is a stochastic agent-based model. We run both models for a range of scenario combinations and compare their projections of spatial and aggregate land use change and ecosystem service supply. We find that the agent-based model projects more multifunctional and heterogeneous landscapes in most scenarios, providing a wider range of ecosystem services at landscape scales, as agents make individual, time-dependent decisions that reflect economic and non-economic motivations. This tendency also results in food shortages under certain scenario conditions. The optimisation model, in contrast, maintains food supply through intensification of agricultural production in the most profitable areas, sometimes at the expense of active management in large, contiguous parts of Europe. We relate the principal differences observed to underlying model assumptions, and hypothesise that optimisation may be appropriate in scenarios that allow for coherent political and economic control of land systems, but not in scenarios where economic and other scenario conditions prevent the normal functioning of price signals and responses. In these circumstances, agent-based modelling allows explicit consideration of behavioural processes, but in doing so provides a highly flexible account of land system development that is harder to link to underlying assumptions. We suggest that structured comparisons of parallel, transparent but paradigmatically distinct models are an important method for better understanding the potential scope and uncertainties of future land use change.

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1 Introduction

Computational models of the land system are essential in supporting efforts to limit climate change and reverse biodiversity loss (Harrison et al. 2018; Rogelj et al. 2018). The need to radically alter human land use to avert social-ecological breakdowns makes modelling particularly useful for exploring conditions that do not currently exist and cannot therefore be observed or otherwise understood (Filatova et al. 2016; IPBES 2018; Smith et al. 2019). In order to make this contribution, the scope and complexity of land system models have been steadily increasing, with many now representing multiple land sectors (e.g. agriculture, forestry and urbanisation) within an Earth System context (e.g. incorporating economic, climatic, hydrological and energy systems) (Harrison et al. 2016; Kling et al. 2017; Pongratz et al. 2018). These models are used not only to explore ranges of scenarios of future change, but also to develop pathways towards sustainability objectives, such as land-based climate change mitigation (Rogelj et al. 2018; Roe et al. 2019; Papadimitriou et al. 2019).

Nevertheless, simulating expected or desired future changes under novel circumstances remains a substantial challenge. Because other methods are not available to generate alternative findings, model results often go unchallenged, and may be misinterpreted as predictions of how the future will develop rather than projections dependent upon underlying assumptions (Low and Schäfer 2020). This could be particularly misleading in social systems such as those underpinning human land use, where no universal laws or predictable patterns exist to guide model development, and modellers must instead choose between a range of contested theoretical foundations, practical designs and evaluation strategies (Brown et al. 2016; Meyfroidt et al. 2018; Verburg et al. 2019).

In this complex context, the proper analysis and interpretation of model outputs is just as important as proper model design. Steps such as standardised model descriptions, open access to model code, robust calibration and evaluation, benchmarking, uncertainty and sensitivity analyses are all necessary to ensure that model results are used appropriately (Baldos and Hertel 2013; Sohl and Claggett 2013). Currently, few if any of these steps are taken universally and rigorously in land use science (van Vliet et al. 2016; Brown et al. 2017; Saltelli et al. 2019). This study focuses on one in particular; the comparison or benchmarking of independent land use models against one another.

Comparison is especially important for land use models because a range of very different conceptual and technical approaches could be valid for simulating social-ecological dynamics (Filatova et al. 2013; Brown et al. 2016; Elsawah et al. 2020). In the absence of fair comparisons, it is impossible to objectively choose between these approaches or to identify the assumptions on which their outputs are most conditional. However, while comparisons of model outputs have been made (Lawrence et al. 2016; Prestele et al. 2016; Alexander et al. 2017), their ability to link particular outputs to particular methodological choices has been limited. Alexander et al (2017), for instance, found that model type explained more variance in model results than did the climatic and socio-economic scenarios, but they were not able to determine exactly why.

Perhaps the greatest challenge to land use model comparisons is the shortage of models that take distinct approaches at similar geographical and thematic scales. Most established models, especially those operating over large geographical extents, share a basic approach that optimises land use against economic, climatic and/or environmental objectives. Technical and

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geophysical constraints are often treated in detail, while social, institutional and ecological factors are rarely included (Brown et al. 2017; de Coninck et al. 2018; Obermeister 2019). Conceptual research suggests that large areas of system behaviour remain under-explored as a result (Brown et al. 2016; Huber et al. 2018; Meyfroidt et al. 2018), with the likely consequence that established findings have implicit biases and blind spots. These can be especially problematic for the simulation of future scenarios in which neglected aspects of land system change become prominent (Estoque et al. 2020).

In this article, we take advantage of the development of two conceptually distinct, but practically equivalent models of the European land system to make a direct comparison between alternative model paradigms. These models, an Integrated Assessment Platform (IAP) and an agent-based model (ABM) share input data to run under the same internally consistent scenario combinations. The former is a constrained optimising economic-equilibrium model and the latter is a stochastic behavioural model. We run both models for combinations of the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) scenarios (O'Neill et al. 2017), and compare their projections of spatial and aggregate land use change and ecosystem service provision. We use this analysis to understand the effects and importance of the different assumptions contained in each model for simulated land use futures, and draw general conclusions about the contributions of both approaches to understanding land system change.

2. Methods

This paper uses two contrasting models of the European land system: CRAFTY-EU (Brown et al. 2019b) and the IMPRESSIONS Integrated Assessment Platform (IAP) (Harrison et al. 2015, 2019). Both models cover all European Union Member States except Croatia, as well as the UK, Norway and Switzerland. The IAP's simulated baseline land use map, land use productivities, scenario conditions and ecosystem service provision levels were used in CRAFTY-EU, making them uniquely equivalent examples of different modelling paradigms. Both models were run for a subset of socio-economic and climatic scenario combinations, and their outputs systematically compared, as described below.

2.1 Model descriptions

The *IMPRESSIONS IAP* is an online model of European land system change that incorporates sub-models of urban development, water resources, flooding, coasts, agriculture, forests and biodiversity. Within this cross-sectoral modelling chain, rural land use is allocated within each 30-year timeslice according to a constrained optimisation algorithm that maintains equilibrium between the supply and demand for food and (as a secondary objective) timber, through iterating agricultural commodity prices (cereals, oilseeds, vegetable protein, milk, meat etc.) to promote agricultural expansion or contraction (Audsley et al. 2015). Calculations are carried out across overlapping geographically unstructured clusters of cells with similar production conditions (based on soil and agroclimate), with profitability thresholds used to determine which land use and management intensity is allocated to each cluster. Land use proportions within each 10' x 10' grid cell represent the aggregations of the solutions for each (up to 40) associated cluster. The IAP runs from a present-day simulated baseline land use configuration to the mid-2080s under combined climatic and socio-economic scenarios. The IAP has been applied and

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evaluated in a large number of studies including sensitivity and uncertainty analyses (e.g. Brown et al. 2014; Harrison et al. 2015, 2016, 2019; Kebede et al. 2015; Holman et al. 2017a, b; Fronzek et al. 2019). A full model description and the online model itself are available at http://www.impressions-project.eu/show/IAP2_14855.

CRAFTY-EU is an application of the *CRAFTY* framework for agent-based modelling of land use change (Murray-Rust et al. 2014; Brown et al. 2019b) that covers the same extent as the IAP at the same (10 arcminute) resolution. CRAFTY uses the concept of Agent Functional Types (AFTs) (Arneth et al. 2014) to simulate land use change over large geographical extents while capturing key behaviours of decision-making entities (agents) that include individual land managers, groups of land managers and institutions or policy bodies (Holzhauer et al. 2019). Modelled land manager agents compete for land on the basis of their abilities to produce a range of ecosystem services that society is assumed to require. In CRAFTY-EU, these services are crops, meat, timber, carbon sequestration, recreation and landscape diversity. Satisfying demands for services brings economic and non-economic benefits to individual agents, with benefits quantified as functions of unsatisfied demand. In this case, these functions are linear and equivalent for all services, meaning that the benefit of production of each service increases equally per unit of unmet demand. Economic benefit represents income from marketable goods and services, and non-economic benefit represents a range of motivations, from subsistence production to the maintenance of societal, cultural or personal values associated with particular services or land uses. Ecosystem service production levels are determined by the natural productivity of the land and the form and intensity of agents' land management, as described in detail in Brown et al. (2019). The outcome of the competitive process at each annual timestep is determined by agent-level decision-making that is not constrained to generate the greatest benefit, and agents are parameterised here to continue with land uses that provide some return rather than abandon their land, but to gradually adopt significantly more beneficial alternatives if available.

Importantly for this study, CRAFTY-EU is parameterised on the basis of the IAP, taking IAP outputs as exogenous conditions and replacing only the land allocation component to provide alternative land use projections under identical driving conditions. CRAFTY-EU is initialised on the IAP's baseline map, and only diverges from that stable baseline 'solution' as scenario conditions change (Brown et al. 2019b). Land use productivities are also calculated from IAP outputs dependent on land use allocation, with the result that productivities are set to zero where the IAP determines production to be economically infeasible. For ecosystem services with economic values (meat, crops and timber), agents in CRAFTY therefore make production choices consistent with this basic level of economic rationality. A full description of the model can be found in Brown et al. (2019) and an online version with access to full model code at https://landchange.earth/CRAFTY.

2.2 Climate and socio-economic scenarios

Seven combinations of climatic and socio-economic scenarios were simulated, based on the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2017). The RCPs and SSPs were combined taking account of internal consistency with their associated greenhouse gas emissions; RCP2.6 was combined with SSP1 and 4; RCP4.5 with SSP1, 3 and 4; and RCP8.5 with SSP3 and 5. The SSPs have been further developed for Europe through a

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stakeholder-engagement process that included interpretation and quantification of key drivers of change in land-based sectors (Kok et al. 2019). For this study, RCPs were simulated in the IAP using outputs from two global-regional climate models (EC_Earth/RCA4 for RCP2.6, and HADGEM2-ES/RCA4 for RCPs 4.5 and 8.5 (Harrison et al. 2019)). Scenario outcomes are described for CRAFTY-EU in Brown et al. (2019b) and for the IAP in Harrison et al. (2019) and Papadimitriou et al. (2019). In addition to these established scenarios, one scenario combination (RCP4.5 – SSP3) was simulated with additional variations in model parameterisations. This scenario was chosen as producing particularly divergent results between the two models, and parameter values were altered to assess whether analogous driving factors led to convergence between the models. Specifically, we increased imports in the IAP by 40% (to mimic an observed under-production of food in CRAFTY), and increased the value of food production in CRAFTY by ten times (to compensate for reductions in supporting capital levels responsible for the under-production of food).

2.3 Comparison

In this study, both models are run until the mid-2080s (defined as a 30-year timeslice in the IAP, and the year 2086 in *CRAFTY-EU*). Both use a spatial grid of resolution 10 arcmin x 10 arcmin (approximately 16km x 16km in Europe), but simulated land classes differ between the two models (as described in Brown et al. 2019b) and are standardised here as described in Table 1, to focus on major, comparable forms of agricultural and forestry management. Other forms of land use and management (e.g. urban land uses) are not compared as they are shared by both models. The labels assigned to these land use classes reflect the dominant form, but not the remaining range, of management within them. We therefore also compare ecosystem service production levels, which account for exact forms of management simulated in each cell.

The comparison of these land use classes was made at two spatial resolutions: across the whole of the modelled domain (without reference to spatial configurations) and across 323 Nomenclature of Territorial Units for Statistics (NUTS2) regions. NUTS2 resolution was chosen for the spatially explicit comparison instead of the original 10’ model resolution to limit the impact of relatively uninformative differences in the allocation of individual cells, and to focus instead on systematic differences in model responses to the simulated scenarios. This choice also reflects the fact that neither model is intended to predict cell-level outcomes, but to provide illustrative realisations of scenario outcomes, with the cell-level results of CRAFTY-EU differing between individual runs because the model is stochastic and path dependent. At NUTS2 level, only differences between the models affecting at least 5% of the relevant cells were included in the analysis. In the following sections (Results and Discussion), CRAFTY-EU is referred to simply as CRAFTY, for brevity.

3. Results

3.1 Aggregate comparison

The responses of the two models to scenario conditions are notably different in most cases (Figures 1 & 2), albeit within similar broad limits (Fig. 1). The greatest similarities in terms of aggregate land use classes occur in the SSP1 simulations, where both models produce land systems that remain similar to the baseline, with large areas of intensive agriculture and small areas of land not managed for agriculture or forestry. The IAP results include more dedicated pastoral land and the CRAFTY results more forestry, with the differences being greatest in RCP2.6-SSP1. In both RCP2.6 simulations, CRAFTY produces an under-supply of food and both models produce an under-supply of timber, though the supply-demand gaps are smaller in RCP4.5, where productivity is slightly higher (Fig. 2). CRAFTY also has smaller differences between food and timber supplies due to its equivalent valuation of all modelled services.

In other scenarios, the IAP responds most strongly to SSPs 4 and 5, while CRAFTY responds most strongly to SSP3. At aggregate level, CRAFTY produces similar results in the SSP4 and 5 simulations as in SSP1 (Fig. 1), though with generally less intensive agriculture and higher supply levels (even exceeding demand in the higher climatic productivities of RCP4.5 and 8.5) (Fig. 2a). In contrast, the IAP projects a dramatic move away from intensive agriculture in SSPs 4 and 5 as a consequence of greatly increased productivity requiring a smaller agricultural area to meet demand. This loss of agricultural management in previously intensively-managed areas is far more pronounced in the IAP than in CRAFTY, where the wider range of valued ecosystem services supports more management and, in some cases, oversupply of services (Fig. 2). As in SSP1, the extent of agricultural abandonment is greatest in the IAP in RCP4.5, where increased yields in some areas reduce the relative competitiveness of agricultural land in less productive areas.

SSP3 produces considerably smaller responses in the IAP, with some areas of all land use types going out of management and with far larger areas of the intensive agriculture class remaining than in SSP4. CRAFTY outcomes for SSP3 are highly dependent on climate scenario, with RCP4.5 producing the strongest response, most notably in terms of a large shortfall in the supply of crops (Fig. 2a). In this case, widespread extensification of land use occurs, with little intensive agriculture remaining by the end of the simulation, and a slight increase in land going out of agricultural or forestry management. In RCP8.5 these changes are less pronounced, with only small changes from intensive agriculture to extensive and forestry management. These changes occur because SSP3 includes deteriorating inherent agricultural productivity and also substantial declines in capital values that support land management (particularly financial, human and manufactured capitals). In CRAFTY, these simultaneous changes make it difficult for agents to maintain intensive management against competition from extensive and less capital-dependent forms of management. The increased yields in some parts of Europe produced by climate change in RCP8.5 make this scenario more conducive to the maintenance of intensive management.

The models also respond very differently to the SSP5 scenario (paired only with RCP8.5). In the IAP, large areas switch to extensive and other/no management classes while there is very little overall change in CRAFTY. The differences between the models' responses are mainly due to the higher yields and improved technological conditions in SSP5 making large areas of

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intensive agriculture surplus to requirements; these are no longer intensively managed for agriculture in the IAP by the 2080s, but are retained in CRAFTY (resulting in over-supply of food) because they provide other services and because of the gradual decision-making of agents.

Together, these scenario results show that the IAP responds most strongly to scenarios with conditions in which agricultural productivity increases, and which therefore lead to reduced need for agricultural land and, in this model, extensification and agricultural abandonment (which occurs over larger extents in the IAP than in CRAFTY). CRAFTY responds less strongly to such conditions because agents have a (parameterizable) unwillingness to change or abandon their land use in the absence of a more viable alternative, and because a wider range of services produce returns for those agents. Conversely, CRAFTY responds most strongly to scenarios in which agricultural productivity decreases because its design emphasises changes in capitals that support production (climatic or socio-economic), as is particularly clear in SSP3. In these circumstances, intensive agriculture is less competitive than extensive agriculture or other multifunctional land uses, and intensive agents are easily replaced (competition is a more rapid process than abandonment in the CRAFTY parameterisation used here).

3.2 Spatial comparison

Within the overall differences between model results exist some consistent spatial patterns (Fig. 3). Across scenarios, the IAP often places more pastoral and very extensive land use classes in western Europe in particular, while CRAFTY often has more intensive agriculture in mid-latitudes and forest in eastern and northern areas (Fig. 3). These differences are very scenario-dependent, however, and as with the aggregate summaries above, the spatial patterns produced by one model in SSP3 resemble those produced by the other model in SSP4. In SSP4, the IAP projects substantially more very extensive and forest management than CRAFTY's more intensive results, while the near-inverse is true for SSP3 (reflecting implicit assumptions that over-production is not penalised, in CRAFTY, and that intensive agriculture retains an efficiency advantage over extensive, in the IAP). CRAFTY also produces a great deal more forest management in RCP2.6-SSP1, with intensive arable agriculture dominating only in the most productive parts of France, Germany and the UK. SSP1 is also the scenario in which the IAP produces the most concentrated areas of intensive pastoral agriculture, particularly in Ireland, the UK and France.

Notwithstanding the smaller-scale fragmentation of land uses in CRAFTY (see below), these results show that at this aggregate level, CRAFTY has a tendency (except in SSP3) to concentrate intensive agriculture in mid-latitudes, extensive agriculture in the southern Baltic states, and very extensive land uses at the European latitudinal extremes. Forestry is distributed in the western UK and central-eastern states in particular. The IAP results are less consistent, but show a tendency to produce pastoral agriculture in the west and forestry more widely. Many of these differences may reflect the valuation of a wider range of services in CRAFTY, leading to a concentration of intensive management in the most productive areas where it can maintain relative competitiveness. As above, they also reflect the differences in the conditions that the models respond to, with the IAP particularly sensitive to changes in demand that do not have spatial manifestations, and CRAFTY more sensitive to capitals that are maximised in climatically suitable, but also politically stable and affluent countries.

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3.3 Convergence experiment

The scenario combination RCP4.5-SSP3 was chosen as having particularly different results from the two models, and so used to examine the potential for convergence in model settings and results. In this scenario, CRAFTY produces a highly fragmented land system with areas of abandoned or extensively managed land scattered throughout Europe, and a substantial shortfall in food production. The IAP, in contrast, produces large contiguous agricultural areas with far more intensive management (albeit of greatly reduced productivity) and less forestry, satisfying food demands.

In terms of overall land system composition the changes in the IAP (an increase of 40% in food imports) did not approach the original CRAFTY results (Fig. 4). While the extent of intensive agricultural management did decrease, this led to widespread agricultural abandonment rather than additional extensive or forestry management (demand for which was already satisfied), with remaining food production being even more concentrated in certain intensively-managed parts of Europe (particularly the East). Large parts of southern and northern Europe fell out of agricultural management, with other regions and countries being managed only for forestry. Other results (above) suggest that the IAP would have more closely resembled the CRAFTY result had there been an explicit driver for extensification, rather than simply an effective decrease in demand levels.

From the more extensively-managed and fragmented initial result produced by CRAFTY, a ten-fold increase in food prices did come closer to the initial IAP result, although with more intensive agriculture and less land under other or no management. The distribution of land uses was strikingly different, however. Unmanaged land mainly occurred in the same areas, and concentrations of forestry overlapped to some extent, but the agricultural land in the CRAFTY result remained highly fragmented across much of Europe. In this case, CRAFTY produced sufficient food to satisfy demand.

4. Discussion & conclusions

Understanding the contributions of different modelling paradigms to land use projections is important for two main reasons. The first reason is that almost all large- to global-scale land system models share a single paradigm (economic optimisation of land uses), raising the risk of biases in model results and resultant, unrecognised knowledge gaps (e.g. Verburg et al. 2019; Elsawah et al. 2020; Müller et al. 2020). The second reason is that different paradigms are known to produce very different outcomes, but for reasons that remain unclear (Prestele et al. 2016; Alexander et al. 2017). The focused comparison presented here is therefore intended to identify and explain key differences between models representing major, distinct paradigms. Neither model is intended to be predictively accurate, but to project land system dynamics on the basis of complex and integrated processes founded on a small number of key, transparent assumptions. Both models have also been extensively used and evaluated, and both respond stably and predictably to driving conditions (Brown et al. 2014; Harrison et al. 2016; Holman et al. 2017b; Brown et al. 2018b; Harrison et al. 2019; Brown et al. 2019b). As expected, our results reveal large and consistent differences between the two selected models that emerge from the different ways in which those models represent land system change.

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An overarching distinction is apparent between the basic assumptions underlying the models. The IAP is an example of a 'top-down' model that simulates change at the system-level – in this case through an assumption of constrained economic optimisation - while CRAFTY is an example of a 'bottom-up' model that simulates change at the level of individual decision-makers – in this case through an assumption of behavioural choices made at the level of local land systems (Brown et al. 2016). This basic difference affects the rate, extent and pattern of simulated land use change. These paradigms usually have different uses and justifications: the (dominant) top-down approach is computationally efficient, tractable and more in line with economic theory, although it is rarely justified as an accurate representation of how land use decisions are made in practice (in fact the evidence tends to contradict it; e.g. Chouinard et al. 2008; Schwarze et al. 2014; Appel and Balmann 2019). The bottom-up approach, in contrast, is more exploratory and often criticised for producing uncertain results, but explicitly attempts to achieve greater process accuracy (Brown et al. 2016).

The consequences of top-down and bottom-up perspectives is apparent in the main forms of land use change as the models respond to scenario conditions. The IAP's consistent profitability thresholds within a deterministic optimising framework respond strongly to increasing yields or decreasing demands, when the model produces widespread agricultural abandonment outside the most productive land. Conversely, CRAFTY's heterogeneous competition process within a stochastic agent-based framework responds more strongly to decreases in productivity, when the model produces extensification and expansion of agriculture. This difference is also apparent in our convergence experiment, where increased imports in the IAP lead to reduced agricultural area, ensuring efficient production where competitiveness is highest, rather than the extensification that CRAFTY produces. Increasing food prices in CRAFTY did generate aggregate land use proportions similar to those of the IAP, albeit with largely distinct spatial distributions, suggesting that agents become more 'optimal' in behaviour when greater competitive advantages are available.

This fundamental difference in dominant land use change trajectories is accentuated by the representation in CRAFTY of individual and societal desires for a range of ecosystem services, which means that extensive management practices that provide recreation, carbon sequestration or landscape diversity, for example, are adopted instead of land abandonment. This is not necessarily tied to model paradigm; optimisation can in principle be performed across a range of criteria, potentially accounting for many more (economically-valued) ecosystem services, although this remains conceptually and computationally challenging (Seppelt et al. 2013; Newland et al. 2018; Strauch et al. 2019). The non-optimising representation used in models such as CRAFTY is closer to the reality of how land use actually changes (Schwarze et al. 2014; Appel and Balmann 2019), but still requires additional parameterisation and rigorous uncertainty analysis (Verburg et al. 2019). In either case, there is strong justification for including a wide range of ecosystem services, particularly those such as carbon sequestration that may gain distinct values in different future scenarios (Kay et al. 2019; Estoque et al. 2020).

One consequence of simulating demand and supply of a range of ecosystem services is that the relative economic support available for food production becomes a key determinant of the balance of different land uses. Models such as the IAP seek to maintain food supplies, even at the expense of other services such as timber production, while models such as CRAFTY allow supply levels to emerge from simulated decisions and so are capable of producing shortfalls. All of the models' results are affected by this basic assumption about whether equilibrium does or will exist in the food system, and further by the extent of disequilibrium that is tolerated and the mechanism by which that extent is defined. For instance, food prices in CRAFTY can respond to shortfalls in production through a number of parametric functions, while the in the IAP prices are automatically adjusted within broad limits to ensure that demand and supply match. However, shortfalls in food production in CRAFTY are not linked to hunger, societal unrest or migration, and food prices in the IAP may become unrealistically high in scenarios where economic and social conditions are very challenging (Pedde et al. 2019; Hamilton et al. 2020). In both models, the simulation of the European land system as distinct from the rest of the world requires implicit assumptions about conditions in other regions and their relationships to Europe. As conceptual alternatives, therefore, neither of these necessarily capture the true dynamics of food prices and production levels, which remains a major challenge for land system modelling (Pedde et al. 2019; Müller et al. 2020).

Beyond differences at aggregate level, another notable feature of results shown above are that CRAFTY produces far more small-scale heterogeneity in land use than does the IAP. This heterogeneity is particularly pronounced in CRAFTY's SSP3 simulations (Fig. 4) and reflects a basic modelling approach: the simulation of distinct cell-level and time-dependent decisions, with agents parameterised here to abandon land only if it provides no returns, and then only gradually. This effectively precludes the system-level optimisation practised by the IAP, which does not account for individual land use decisions. Individual-level heterogeneity is, inevitably, very difficult to parameterise precisely, although participatory techniques have some promise in this respect (Elsawah et al. 2015). Conversely, (constrained) optimising models like the IAP produce idealised results that may not replicate observed rates or spatial structures of land use change (Turner et al. 2018; Brown et al. 2019a; Low and Schäfer 2020), but can use flexible spatial dependencies as proxies for processes such as imitation, diffusion of knowledge or the formation of social norms (Meiyappan et al. 2014; Brown et al. 2018a).

Notwithstanding the gains to be made by better understanding the relative performance of different model paradigms, it is essential to recognise some hard limits. No land use model is intended or able to provide calibrated representations of all the mechanisms responsible for land use change, especially under imagined future conditions. Both alternatives must therefore be seen as providing realisations of assumptions that are useful in some ways but incorrect in others. Optimising models have the advantage of representing idealised conditions, but not necessarily the pathways by which those conditions can be reached (Ligmann-Zielinska et al. 2008; Low and Schäfer 2020). Process- or agent-based approaches, meanwhile, can allow exploration of the large behavioural uncertainties involved in the simulation of human systems, and can be powerful tools for stakeholder engagement and understanding (Millington et al. 2011; Low and Schäfer 2020) – but are unlikely to perform any better at predicting system outcomes than simpler, more tightly constrained models (Salganik et al. 2020). Indeed, their primary strength may be their ability to use theory as a guide to processes and conditions that empirical data and optimising models do not cover (Gostoli and Silverman 2020).

The greatest value of these two approaches may therefore lie in their ability to provide alternatives; a value that is realised only in the (currently rare) cases when model assumptions are clearly communicated and when analogous models such as those used here are available for comparison (Polhill and Gotts 2009; Müller et al. 2014; Rosa et al. 2014). Further benefits can be drawn from combinations of the two modelling approaches, although this usually involves an artificial choice of systems or scales at which top-down optimisation and bottom-up emergence are assumed to occur (e.g. Castella and Verburg 2007; Verburg and Overmars 2009; Houet et al. 2014). In addition, the benefits of using each type of model can be maximised (and the differences between them potentially minimised) by flexible multi-criteria optimisation on one hand and behavioural uncertainty analysis on the other (Fonoberova et al. 2013; Ligmann-Zielinska et al. 2014; Newland et al. 2018; Brown et al. 2018b). Both can also be advanced by new interdisciplinary approaches to better represent qualitative knowledge about land system change (Elsawah et al. 2020). Such interdisciplinary approaches could, for instance, allow integration across the individual, societal and even political levels, using different or flexible modelling approaches at each level to improve their representation (e.g. Andersen et al. 2017). Technically, integration of this kind can utilise powerful forms of 'hybrid' modelling that allows model design and complexity to be tailored to requirements (Parrott 2011; Lippe et al. 2019). In allowing parallel or integrated usage of different paradigms, all of these methods can provide insights that suffer less from individual weaknesses, and benefit more from individual strengths, than each model in isolation. Substantial efforts to increase both the diversity and coherence of land system modelling are likely to be necessary if these important gains are to be made.

Code and data availability

The full model code and data for CRAFTY-EU are available for download and visualisation via https://landchange.earth/CRAFTY

The IAP is available for interactive online runs at http://www.impressions-project.eu/show/IAP2_14855 but model code is not available because the IAP utilises meta-models of several other stand-alone models under different ownership.

Appendices

Appendix A: Land use class composition

Author contribution

CB performed the analysis and drafted the manuscript; IH & MR assisted with planning, interpretation and writing.

Competing interests

The authors declare that they have no conflict of interest

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Land use classes for comparison	**Explanation**
Intensive agriculture	Intensive forms of agriculture primarily dedicated to crop production but including some grassland
Extensive agriculture	Extensive forms of arable and pastoral agriculture
Pastoral agriculture	Dedicated and primarily intensive pastoral agriculture
Very extensive management	Management for any service that is of the lowest intensity and leaves land in a near-natural state
Forestry	Active management for timber extraction and other forest services
Other/no management	Land that is not actively managed for agriculture or forestry, but which can have a range of natural or human-impacted land covers

Table 1: Land use classes used in the comparison and their composition. Derivations from the full range of CRAFTY and IAP classes are given in Table A1.

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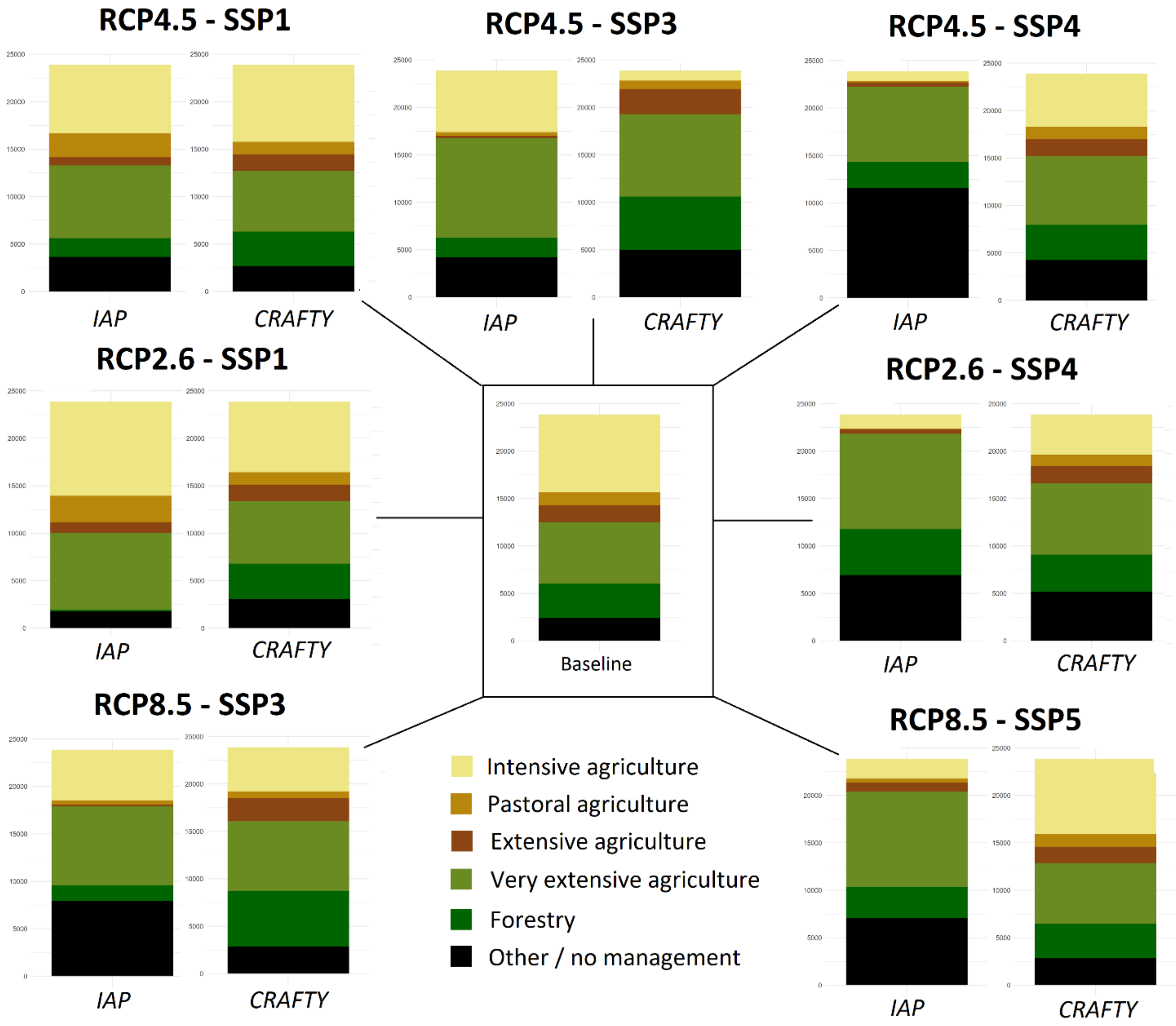

Figure 1: Simulated land use classes for each scenario in each model in the mid-2080s.

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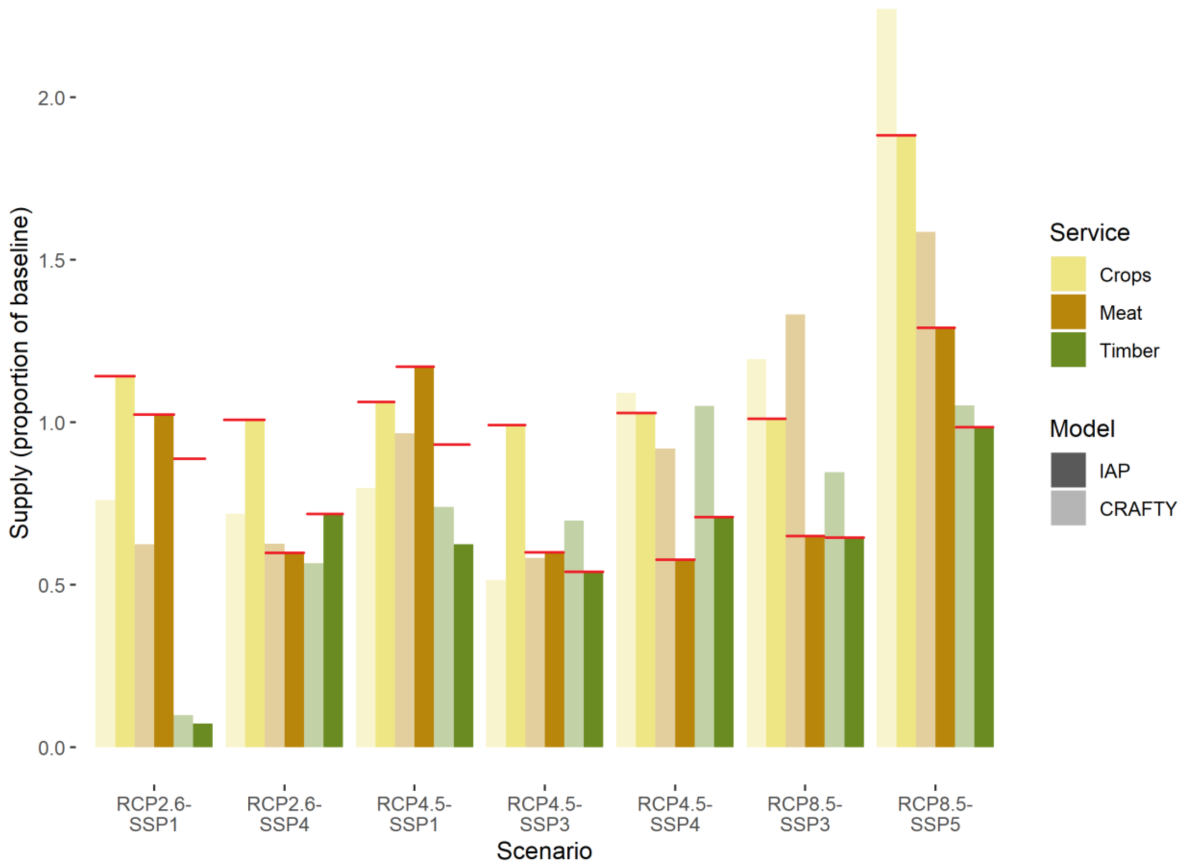

530 **Fig. 2a: Supply levels of services actively modelled in both models, in each scenario. IAP supply levels are linked to scenario conditions and are set as demands for CRAFTY by default, after being calculated using CRAFTY production functions to ensure comparability. IAP supplies are unequal to demand levels only where the IAP reports an underproduction of a particular service (in these results, timber in SSP1 simulations). A supply value of 1.0 (y-axis) is equal to baseline supply, and the scenario-specific demand level for each service is shown in red.**

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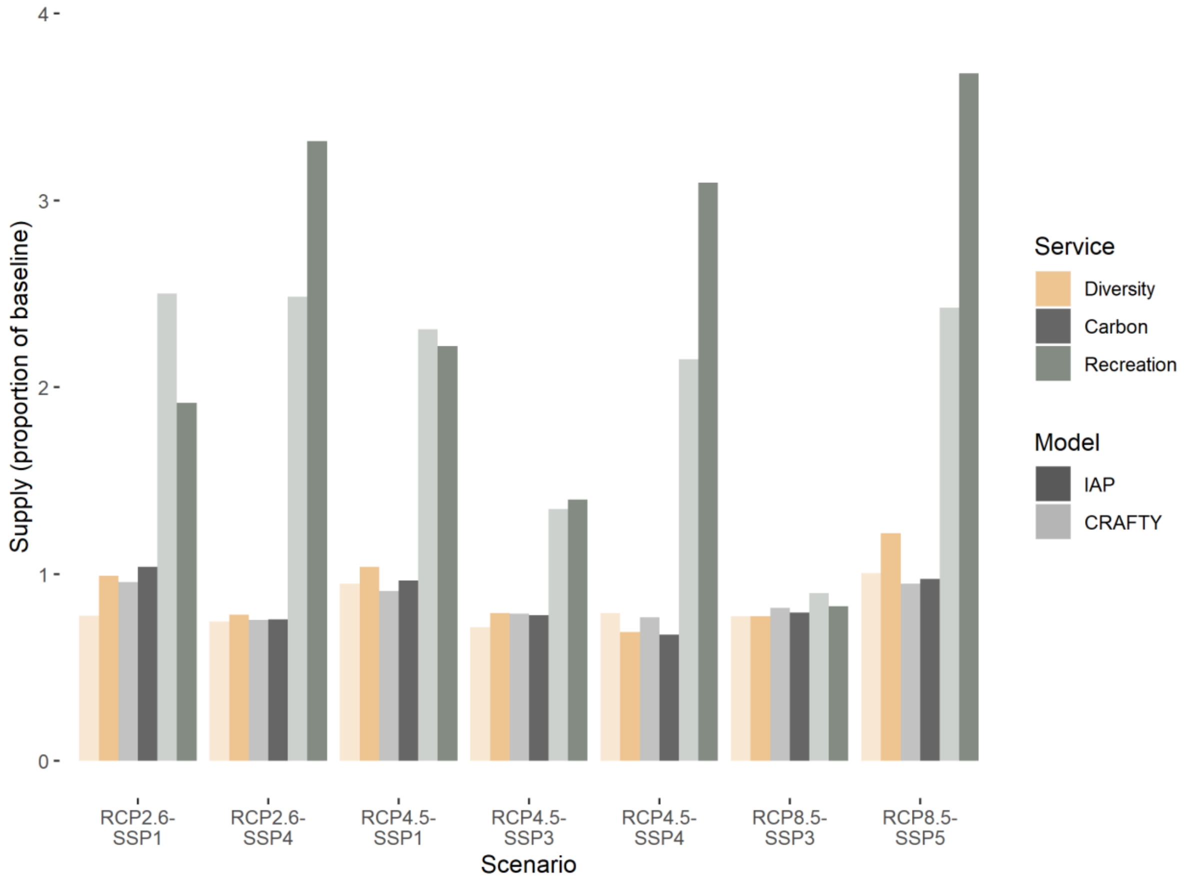

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Fig. 2b: Supply levels of services with no defined demands in the IAP. IAP supply levels here are calculated using CRAFTY production functions and then set as demands for CRAFTY, with production having equivalent value to the three primary services (Fig. 2a). The IAP therefore does not attempt to achieve particular supply levels for these services, while CRAFTY does.

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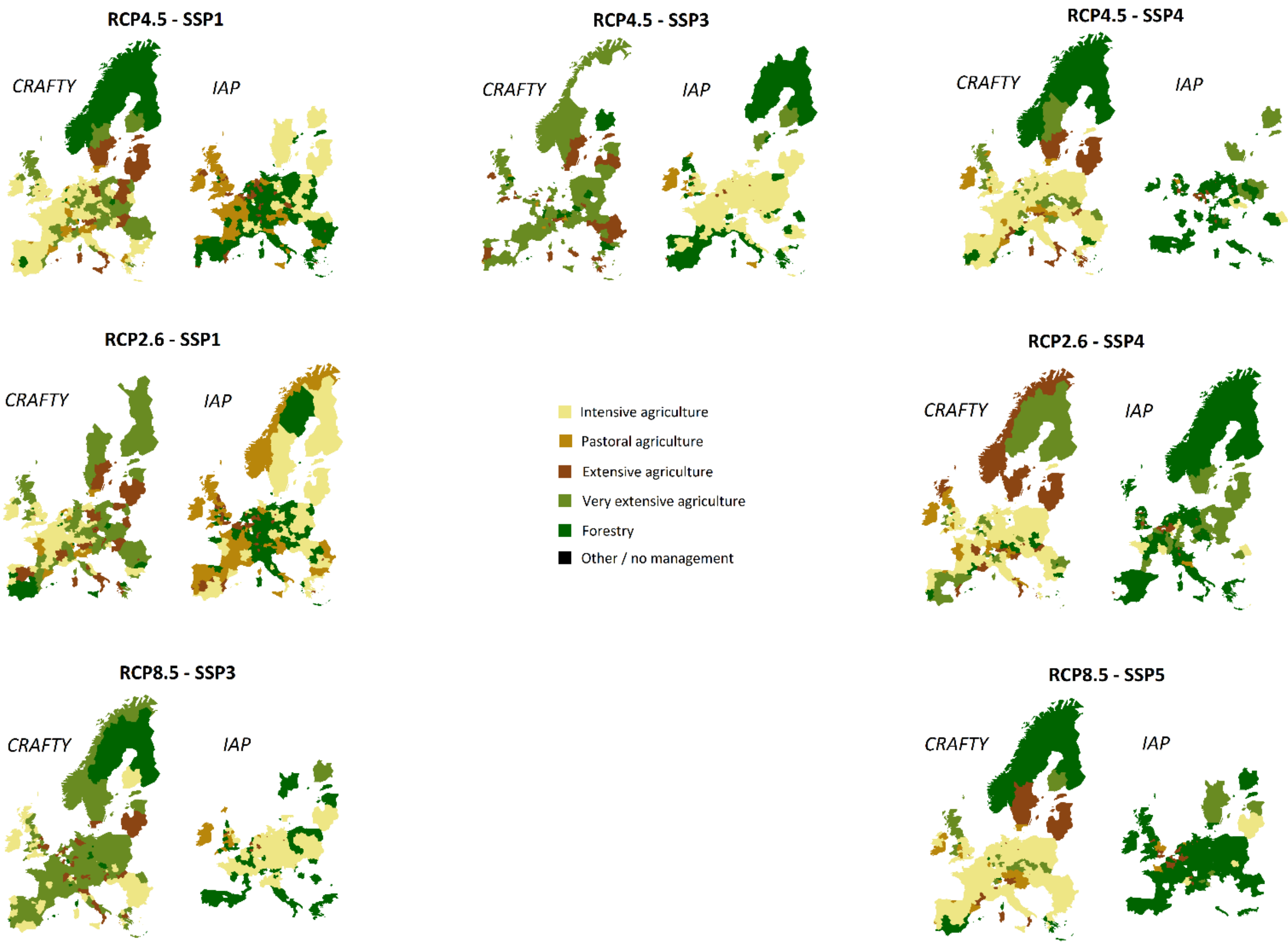

Fig 3: Spatialised differences between the models' results for each scenario, at NUTS2 level. Colours identify the most over-represented land use type in each region in the CRAFTY and IAP results, relative to the result of the other model. White is shown where no land use type has an over-representation of more than 5% of the region's cells.

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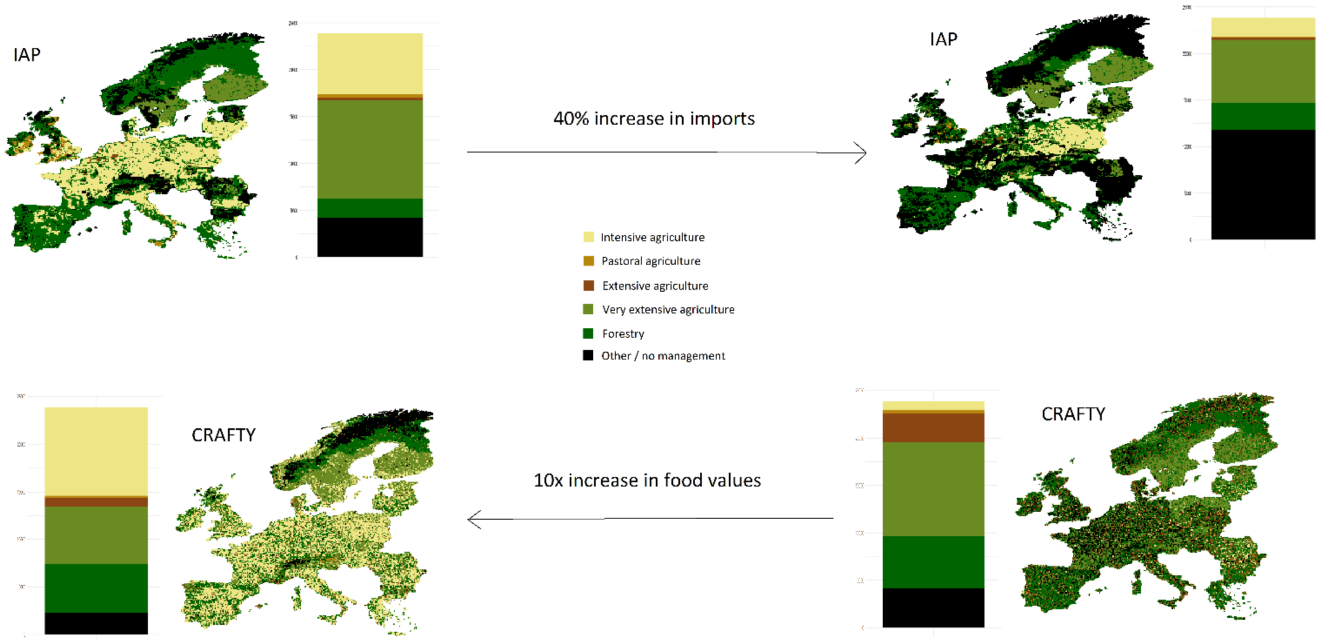

Fig. 4: Cell-level and aggregate results for the RCP4.5-SSP3 scenario with and without alternative parameterisations designed to introduce analogous driving conditions to each model in turn.

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Appendix A: Land use class composition

Ecosystem service production in CRAFTY is derived from that of the IAP, which uses a suite of meta-models to simulate production levels as described in (Harrison et al. 2019), and is presented in detail in Brown et al. (2019). CRAFTY-EU also shares a baseline map with the IAP, with the aggregated land use classes used here derived from CRAFTY's Agent Functional Types (AFTs) and the IAP's land use classes as described in Table A1.

Agent Functional Type	IAP Class	Aggregated class
Intensive arable farming	Intensively farmed	Intensive agriculture
Intensive agro-forestry mosaic	Combinations of: Intensively farmed, intensively grass, managed forest	
Intensive farming	Combinations of: Intensively farmed, intensively grass	
Mixed farming	Combinations of: Intensively farmed, intensively grass, extensively grass	
Managed forestry	Managed forest	Forestry
Mixed forest	Combinations of: Managed forest, unmanaged forest	
Mixed pastoral farming	Combinations of: intensively grass, extensively grass, very extensively grass	Extensive agriculture
Extensive agro-forestry mosaic	Combinations of: extensively grass, very extensively grass, managed forest	
Peri-urban	Any combination with > 40% urban area	
Intensive pastoral farming	Intensively grass	Pastoral agriculture
Extensive pastoral farming	Extensively grass	
Very extensive pastoral farming	Very extensively grass	Very extensive management
Multifunctional	4 or more land uses in uncommon combination	
Minimal management	Combinations of: very extensively grass, unmanaged forest, unmanaged land	
Unmanaged land	Unmanaged land	Other/no management
Unmanaged forest	Unmanaged forest	
Urban	Urban	

Table A1: The composition of the aggregated land use classes used here in terms of CRAFTY-EU's Agent Functional Types (AFTs) and the IAP's land use categories. In any case where the given IAP categories occupy more than 70% of a cell, that cell is allocated to the corresponding AFT in the baseline map of *CRAFTY-EU*, except in the case of the Peri-urban AFT, for which the threshold (of urban area) is 40%. The service production potentials of each AFT are calibrated to approximately match those within the IAP classes that constitute them, so that given the same productivities in a cell, the same levels of services will be produced. Names are therefore assigned in both cases on the basis of dominant land uses and do not account for minor variations in land use and production within them.