MagnetGrid

Model description and user guide

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MagnetGrid is een modulair economisch landgebruiksmodel dat ruimtelijk expliciete biofysische informatie combineert met macro-economische projecties. MagnetGrid visualiseert toekomstige agrarisch landgebruikspatronen gedreven door een combinatie van klimatologische en socio-economische ontwikkelingen. Het model kwantificeert de impact van deze trends en de mogelijke uitruil tussen verschillende doelstellingen. De ruimtelijk expliciete analyses van MagnetGrid kunnen voor een breed publiek toegankelijk gemaakt worden door kaarten die veranderingen in landgebruik laten zien op wereld-, regio-, land- en lokaal niveau.

MagnetGrid is a modular economic land-use model adding spatial detail to macroeconomic foresight. It projects and visualises future agricultural land-use change patterns that may emerge from a combination of climatic and socio-economic developments, quantifying the impacts resulting from these trends and evaluating their potential trade-offs across multiple dimensions. Being spatially explicit, results from MagnetGrid can be visualised for a non-technical audience through maps showing the changes in land use at global, regional, country and local levels.

Key words: macro-economics, foresight, agricultural land use patterns, spatial visualisations

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Executive summary

MagnetGrid is a modular economic land-use model adding spatial detail to macroeconomic foresight. Its innovative feature is to combine detailed spatially explicit biophysical information on the suitability of land for specific agricultural activities, with projections of agricultural product and input prices reflecting economy-wide changes over time. Hence, MagnetGrid projects and visualises future agricultural land-use change patterns that may emerge from a combination of climatic and socio-economic developments, quantifying the impacts resulting from these trends and evaluating their potential trade-offs. The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a global model with country-level resolution capturing all global interactions among producers (in agriculture, food processing, manufacturing and services) and consumers linked through price and income feedbacks. MagnetGrid combines these national-level foresight results with biophysical characteristics of land units, determining their suitability for different types of agricultural activities (climate, topography and soil quality).

MagnetGrid can show localised economic impacts from diverse drivers like income growth, changes in diet, climate change, policy reforms (taxes and subsidy schemes), climate mitigation or adaptation. It does this by projecting future land-use patterns regarding not only the profitability of single activities, but weighing these against the sunk costs of past investments and opportunity costs of foregone alternative activities, while respecting the total projected change in land area. This fourfold interaction between the past and future characteristics of spatial units and macro-level projections provides a consistent approach to project land-use developments under different scenarios, doing justice to both the projected macro-level changes and the warranted reluctance of producers to radically transform their business with every small change in prices. Being spatially explicit, results from the MagnetGrid can be visualised from a non-technical perspective through maps showing the changes in land use at global, regional, country and local levels.

MagnetGrid has been developed in a modular form allowing for different regional and sector aggregations in MAGNET and can thus be tailored to the situation at hand. It also permits the use of MagnetGrid with other models, either economic agricultural models to replace MAGNET results or via use of projected changes in crop suitability maps from spatially explicit biophysical models.

1 Introduction

Land is a critical resource, providing the basis for production of food, feed, fibre, timber, energy and many other ecosystem functions and services, including cultural and regulating services, that are essential for humanity (IPCC, 2019). In the coming decades, agricultural land systems are expected to face a multitude of complex sustainability challenges. Firstly, more food will have to be produced in order to feed a rapidly growing world population with changing diet preferences (Tilman et al., 2011, OECD/FAO, 2016). However, this will have to be achieved in the context of increased competition for land with other uses (Smith et al., 2010), while simultaneously attempting to reduce the negative environmental impacts of intensive agricultural activities, such as degradation of soil and water resources (Bennett et al., 2001; Wood et al., 2000), widespread biodiversity loss and degradation of ecosystem services (Kremen et al., 2002; Nagendra et al., 2013) and climate change. Agriculture currently accounts for roughly a quarter of total anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014), and is thus one of the main drivers of global environmental change (Ericksen et al., 2009). GHG emissions from agriculture include both direct emissions occurring at various stages of the production chain (Smith et al., 2008), and indirect emissions resulting from the manufacturing of essential production inputs (Oertel et al., 2016). Net carbon emissions may also occur due to changes in land cover and use resulting from the expansion of agricultural activities into natural areas, particularly those affecting large carbon sinks such as forests and peatlands (FAO, 2016; Oertel et al., 2016). Hence, GHG emissions from land and food production will have to be reduced, together with other sectors, in order to keep global warming below 2 °C (IPCC, 2019).

In turn, global climatic changes feed back on the local biophysical conditions, potentially affecting both crop yields (Rosenzweig et al., 2014) and water availability for agriculture (Elliot et al., 2014). Even though mid- and high-latitude regions might experience positive impacts in some crops as a consequence of higher temperatures and CO_2 levels (Wolfe et al., 2008; Wolf et al., 2011), most impacts are expected to be strongly negative, particularly those resulting from more frequent extreme weather events (e.g. heat waves, droughts and high levels of precipitation) and related emergence of pests and diseases (Gregory et al., 2009; Iglesias et al., 2012, Porter et al., 2014). A changing climate can thus lead to changes in land use and land cover, as farmers may shift to crops that will have a higher economic return under changing climatic conditions or expand production to non-cultivated areas in order to compensate for loss of productivity (Verburg et al., 2013). Furthermore, variations in the availability and quality of water resources may lead to conflicts in the allocation of water for different uses (e.g. agriculture, industry, energy production, drinking water and nature).

Hence, agriculture both contributes to and is affected by climate change. Innovative socio-technical solutions are needed to cope with these challenges in order to achieve the targets on food security, access to water and climate change set forth by the UN’s Sustainable Development Goals (SDGs). For example, sustainable intensification technologies (e.g. crop genetic improvement, precision agriculture and integrated pest management) can potentially increase long-term productivity while improving resource- and input-use efficiency, and minimising both pressure on land and environmental externalities (Smith, 2013). Circular economy strategies can help to avoid food losses and improve waste management, thus potentially decreasing GHG emissions and reducing pressures on the use of land and water for food production (WEF, 2018). Solutions explicitly accounting for the water-food-energy nexus hold promising prospects to anticipate potential trade-offs and synergies across sectors and thus improve cross-sectoral integration and resource-use efficiency (FAO, 2014).

However, finding the solutions that can best facilitate the sustainable provision of food, feed and bioenergy is highly site-specific, depending on the local biophysical and technologic characteristics of the existing production systems, available technological innovations, political and socio-economic contexts, prevalent risks and the means to offset them (Godfray et al., 2010). While most of these drivers operate on wider global scales, the extent to which agricultural systems will be able to balance trade-offs and manage risks will largely depend on the aggregated effects of the strategies adopted at the local and regional levels (Verburg et al., 2013). Coherent solutions to address future food security thus require multidisciplinary approaches that explicitly address the multiple dimensions of agricultural systems.

New tools are therefore needed to identify and quantify potential trade-offs and synergies in agricultural land systems, in order to inform the dialogue between policymakers and stakeholders, and guide the development of cross-sectoral policies that enable an effective governance of these challenges. Such tools should be able to take into account the complex multilevel interactions between biophysical, technological, economic, political and socio-cultural factors explicitly, in order to provide integrated analyses of agricultural systems that are both local-specific and contextualised in their wider regional and global contexts. They should also allow the economic feasibility of different strategies to be quantified and compared under alternative scenarios, identify their (institutional) enablers and barriers, and evaluate their wider impacts in the environment, economy and society (e.g. reduction of GHG emissions, welfare gains, food security and water availability for different uses), while taking into account the territorial dimension of the availability, provision and consumption of resources.

In this context, the Wageningen Economic Research (WEcR) institute has developed MagnetGrid, a global multimodel framework that simulates the spatial patterns of agricultural land use resulting from economic decisions on the use of land. MagnetGrid explicitly takes into account the complex interplay between factors operating at multiple levels in agricultural systems, to explore how they jointly affect land-use decisions and their outcomes. It does so by combining future scenario-based projections on the supply, demand, prices and production costs of different agricultural commodities (as simulated, for example, with global general equilibrium models such as MAGNET; see Woltjer and Kuiper, 2014) with spatially explicit projections on the biophysical suitability for agricultural production (as simulated, for example, with gridded crop growth models such as LPJmL; see Schaphoff et al., 2018). Hence, MagnetGrid allows the projection and visualisation of future agricultural land-use change patterns that emerge from climatic and socio-economic developments under a set of conditions that are specified in scenarios. It is able to simulate the effects of discontinuities explicitly, such as the emergence of new land-use types (e.g. second-generation biofuel crops), the effects of nonspatial policies affecting the economic performance of production systems (e.g. subsidy schemes, tax reductions/exemptions and removal of trade barriers), and the economic decisions leading to the adoption of innovative agricultural practices.

MagnetGrid is largely based upon the land-use modelling framework proposed in Diogo et al. (2015). In its current configuration, MagnetGrid is able to downscale MAGNET’s regional projections on the use of land for the production of agricultural commodities, and provide scenario-based map projections of agricultural land-use change, both at the global level and for dedicated case studies at the regional/country level. MagnetGrid applies a continuous/probabilistic allocation algorithm, according to which each unit of land (e.g. a regular gridcell) within a region is allocated a percentage for each simulated land-use type (indicating the share of total area of the gridcell that is used by that land-use type), so that the scenario projections for total aggregated land claims in a region (e.g. as projected by MAGNET) are simultaneously fulfilled for all simulated land-use types. An operational demo version of MagnetGrid has been deployed that simulates agricultural land use at a 10 km spatial resolution based on MAGNET projections. The configuration of the model is based on templates – a modelling approach that ensures a high degree of flexibility, so that different scenario alternatives and configurations (e.g. combination of crop types into sectors, aggregation of countries into simulation regions) can be seamlessly and efficiently accommodated.

This report describes the MagnetGrid land-use model and provides a user guide for model users and developers. The report is structured as follows. In Part I, an extensive description of the model is provided, including its theoretical background (Section 2), its multimodel land-use modelling framework (Section 3), the underlying spatial land-use model (Section 4) and allocation algorithm (Section 5), the method for specifying the model using MAGNET scenario projections (Section 6) and an overview of the model workflow and structure (Section 7). In Part II we provide a user guide, including a description of the software requirements and installation guide for the different model components (Section 8), the requirements for spatial data (Section 9) and a set of instructions on how to run the model and configure a new scenario (Section 10). To conclude, in Section 11 we provide a list of potential improvements and directions for further development of the model framework as final considerations.

PART I
Model description

2 Conceptual framework

MagnetGrid is largely based upon the conceptual framework for agricultural land-use modelling outlined in Diogo et al. (2015), which in turn draws inspiration from land system science, an emerging field of knowledge that combines concepts and methods from different disciplinary traditions (e.g. geography, landscape ecology and economics) for monitoring and describing patterns of land cover change, explaining drivers of land-use change, and understanding the linkages between these two (Verburg et al., 2015; Meyfroidt et al., 2018). The proposed framework is conceptually rooted in economic theory, and aims to explain the causal links between economic decisions and the resulting spatial patterns of agricultural land use. It applies a combination of Alonso's bid rent theory of land use (1964) and McFadden's discrete choice theory (1978) for guiding the characterisation of land-use change processes. The conceptual framework is briefly summarised here; we refer to Diogo et al. (2015) for a more detailed account on the framework, and Diogo (2018) for an in-depth discussion on the pros and cons of applying a framework based on economic theory to agricultural land-use modelling.

In economic theory, land is regarded as a special asset providing space for locating economic activities, infrastructure and dwellings, as well as delivering production functions, amenity services and aesthetic value (Hubacek and Van den Bergh, 2002). Every land parcel has a fixed location with unique biophysical features and accessibility attributes that determine, to a large extent, its ability to provide vital resources such as food, fuel and raw materials, and many other services that support production functions and regulate natural hazards (Bürgi et al., 2004; Geist et al., 2006). Human interventions, by means of land management practices and technological innovations, are capable of dramatically transforming land's natural endowments, and consequently, enhance or debilitate the potential ability of a location to deliver different functions, services and amenities, often with significant synergies and trade-offs among them.

Land-use changes follow from the decisions that actors (e.g. farmers, property developers and nature managers) make in managing land. Alonso's bid rent theory stipulates that, in a competitive land market, land users seek to maximise their utility, being land purchased/rented by the bidder offering the highest bid, i.e. the potential land user able to derive the highest net benefits from the land. In turn, the utility derived from land depends on the preferences of economic agents for specific objectives and on the degree to which those objectives can be achieved on a specific location (Keeney, 1969). For instance, every farmer has certain objectives that they strive to achieve while engaging in crop production (e.g. increasing profit/income levels, expanding the business, having more leisure time). Within the restrains of their knowledge, available opportunities, potential risks, and access to resources, capital and markets, farmers evaluate different production alternatives and resource allocation options, being expected to choose the options that maximise their overall utility (Rae, 1977; Öhlmér et al., 1998).

McFadden's discrete choice model attempts to explain and predict the outcome of the decision-making processes of economic agents when choosing among mutually exclusive alternatives. The discrete choice model assigns probabilities for the different alternatives according to the utility of each alternative in relation to the total utility of all alternatives. Bid price maps, based on the spatially explicit valuation of local utility of different land-use alternatives, can be used to express the willingness to buy/rent a location for each of the group of actors representing a sector that influences land use. These maps can then applied to the discrete choice model, so the probability of each land-use alternative being chosen can be assessed in each location (Koomen et al., 2015). By coupling together bid rent and discrete choice theories, it is possible to describe the land market clearing process: in each location, a land seller compares alternative bids and sells the land parcel to the actor with the highest bid, thus maximising both revenue of sellers and utility of buyers (Martinez, 1992). Land is thus expected to be used for the purpose which brings the greatest utility, taking into account the relative benefits of alternative land uses (Fujita, 1989). This generally implies that urban development tends to outcompete agriculture. Higher revenue activities such as commerce and services tend to concentrate at the city centre, while industrial and housing functions select locations in its surroundings. A similar process can be observed within the agricultural sector, where capital- and resource-intensive types of farming, such as horticulture, normally outcompete arable farming and husbandry (Bakker et al., 2011).

The utility that can be derived in each location depends, in turn, on a complex combination of spatial and nonspatial factors that together set the opportunities and constraints for different production options (Diogo et al., 2015), for example: spatial factors such as historical land-use trends, accessibility and local biophysical features (e.g. soil properties, climate, topography), economic conditions (e.g. demand, market prices and cost of production factors of agricultural commodities), socio-cultural characteristics (e.g. demography, traditions and preferences), political regimes (subsidies, tariffs, spatial zoning and property rights) and available technology for agricultural production (Fig. 1). Some of these factors (so-called underlying factors) determine the systemic conditions that influence the trajectory of land use, i.e. the amount of land area that is claimed for the production of agricultural commodities, by influencing the use of resources and the consumption of goods (Geist et al., 2006). Others (so-called proximate factors) dictate the local decisions on the use of land and resulting spatial distribution of agricultural land claims, by affecting productivity and related cash flows, and thus determining the overall local utility.

The interplay between proximate and underlying factors appears to drive land-use decisions in a synergetic way, with large variations caused by local conditions and activities, and specific contexts at the regional and global levels (Verburg et al., 2015). For instance, the biophysical suitability for cultivating different crops largely determines the yields that are feasible to achieve locally with the available technology (Van Velthuizen et al., 2007). Farmers evaluate the feasibility and profitability of different production options, taking into account their required investments, production costs, expected revenues from selling the commodities and eventual policy incentives (Rae, 1977; Öhlmér et al., 1998). Concurrently, underlying factors such as demography, income and diet largely determine the global demand for agricultural commodities (Verburg et al., 2008). Price formation processes are established in agricultural markets according to the supply and costs of production from different world regions, and the global demand for agricultural commodities. A trade balance and structure emerges in global agricultural markets, as a result of comparative advantages between regions and trade policy agreements (Miljkovic, 1999; Van Meijl et al., 2006).

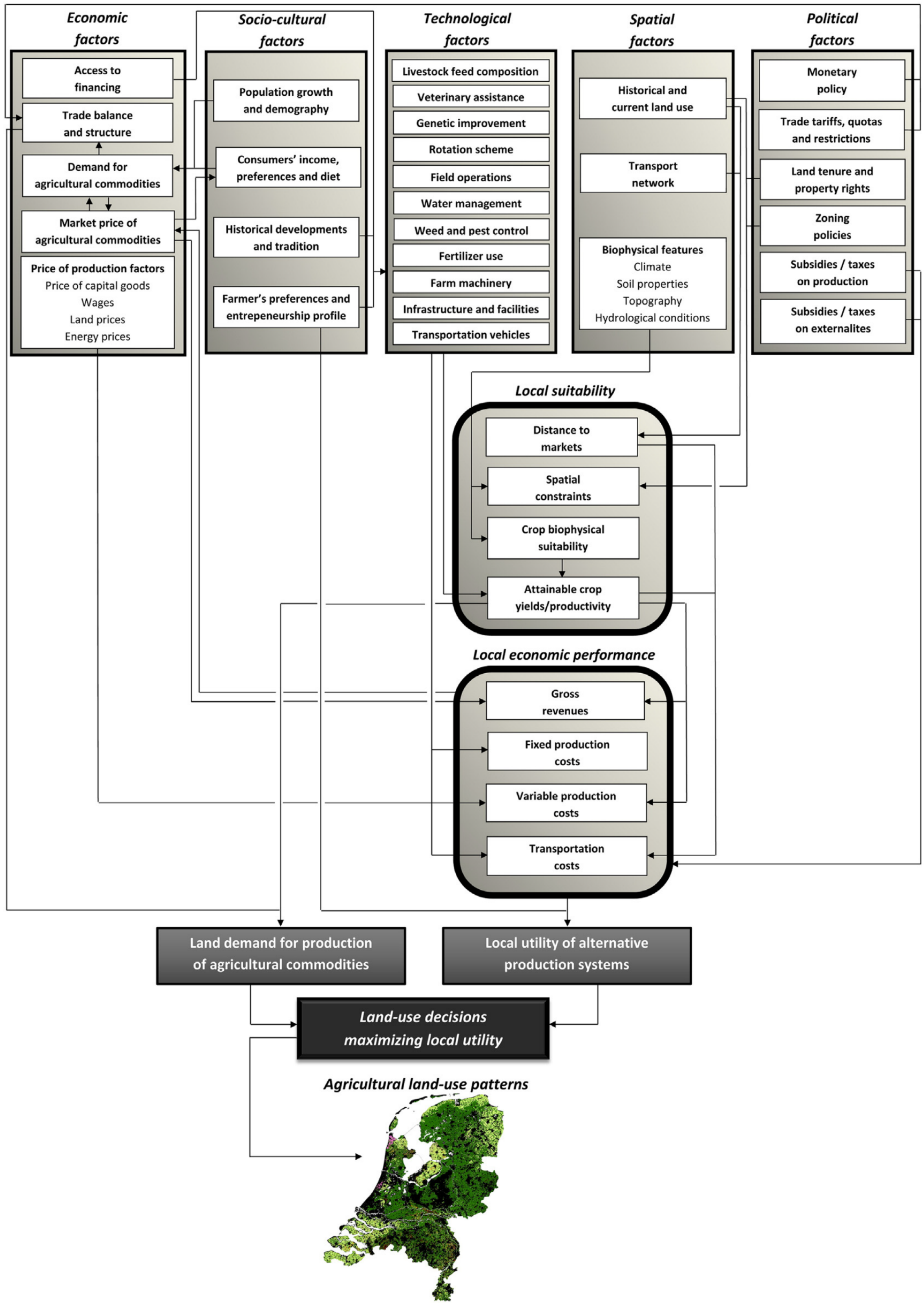

Figure 1 *Conceptual framework for the simulation of agricultural land-use patterns in MagnetGrid (based on Diogo et al., 2015)*

Further developments on socio-economic conditions, climatic changes, technological innovations, deployment of infrastructure, policy reforms, changes in institutional arrangements and (spatial) planning regimes may subsequently affect the conditions determining the supply, demand, prices and production costs of agricultural commodities. Farmers and consumers may then consider adjusting their choices as a response to these variations, depending on the magnitude and/or duration of their effects. Sudden perturbations do not necessarily have to result in an immediate change in the structure of agricultural systems though. For instance, in the case of a temporary fall in the prices/productivity of a certain crop or introduction of a subsidy promoting a new crop, farmers might decide to wait a few years in order to gain better information before changing their cropping system. Such choices may, for example, depend on the investments already made and the degree of flexibility to reverse their decisions (Isik and Yang, 2004; Song et al., 2011; Regan et al., 2015).

The combination of multiple individual land-use decisions over time and across space ultimately leads to the emergence of changes in the patterns of land use (Verburg et al., 2013; Bakker et al., 2011). The net effect of the aggregated changes resulting from farmers’ adjustments in their land management practices may then feed back into the conditions surrounding agricultural production (e.g. by mitigating/contributing to climate change) or in the trade balance of agricultural commodity markets, which in turn can affect ensuing decision-making processes (Rounsevell et al., 2014). Agricultural land systems can thus be interpreted as complex adaptive systems (Parker et al., 2003) manifesting nonlinear behaviour, inertia to change, path dependency of system evolution, feedback loops and spatial interactions in which local developments affect and are affected by conditions in distant locations (Liu et al., 2013; Verburg et al., 2015). Therefore, changes in land systems cannot be simply explained as the equilibrium result of a set of driving forces at a certain moment in time (Verburg et al., 2006).

3 A multimodel land-use modelling framework

Following the conceptual framework presented in Section 2, agricultural land-use patterns are presumed to emerge from multiple land-use decisions aiming to maximise local utility, which in turn are explained by two concomitant processes (see Fig. 1):
- Farmers evaluating the utility of alternative production options, according to the local economic performance of these options and farmers' own objective preferences;
- The regional land claims for different production options arising from the demand for agricultural commodities in the global economy.

These processes depend on a complex combination of underlying and proximate factors operating across scales, which cannot be captured within a single model. Similarly to previous multiscale land-use modelling approaches (see e.g. Verburg et al., 2008), MagnetGrid's modelling framework relies on a series of outputs from various specialised models to account for the cross-scale interplay between proximate and underlying factors at their relevant levels (Fig. 2).

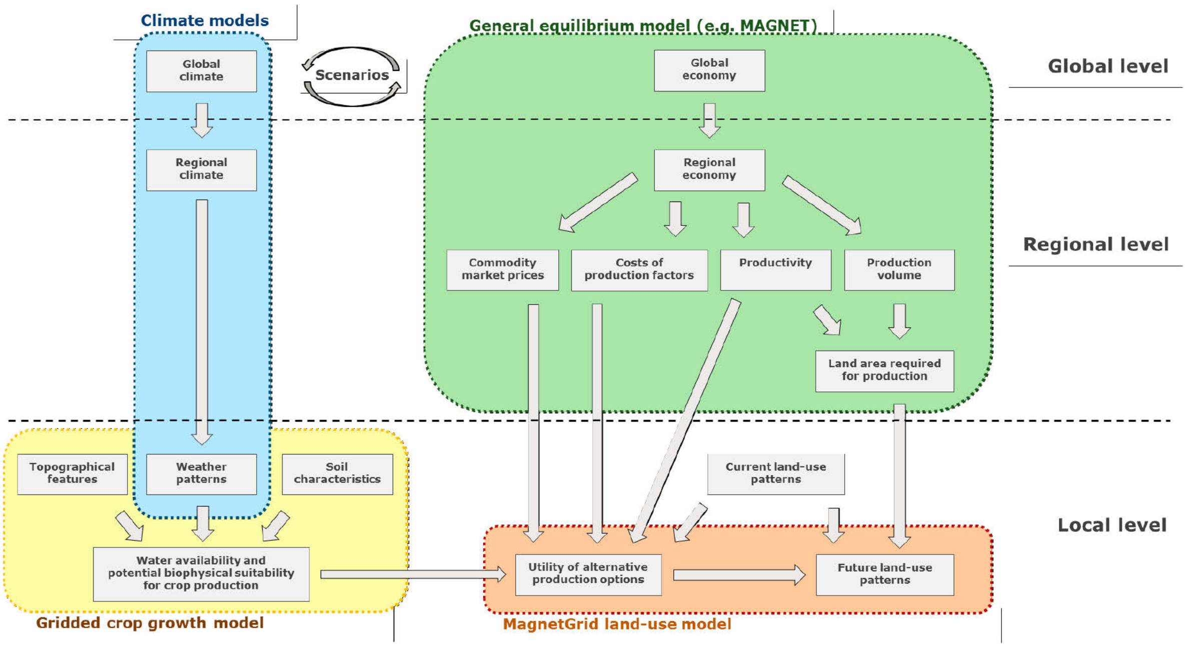

Figure 2 *MagnetGrid's multimodel framework for the simulation of agricultural land-use patterns*

The first step of the methodology is the formulation of scenarios outlining potential future developments in the global economy and climate, according to expected trends in demography, diet, resource consumption and policy regimes. These scenarios usually entail simulating the interactions between the socio-economic and climatic systems by means of quantifying, for example, the effects of anthropogenic greenhouse gas emissions on the global climate and/or the impacts of climate change on the global economy.

The potential developments in the global climate resulting from these trends can be captured by general circulation models (GCM) that are able to simulate the global patterns of atmosphere and ocean circulation under changing conditions (for an IPCC review of climate models, see for example Flato et al., 2013). Global climatic changes affect regional climate conditions, and consequently the daily weather patterns observed at the local level. The projections obtained with GCMs can be further downscaled to the regional level with regional climate models that are able to represent important atmospheric physical processes (e.g. orographic rainfall) with a higher spatial resolution (see for example Giorgi et al., 2009), and then translated into future local weather patterns through statistical downscaling (Blanke et al., 2016). Projections on local weather patterns, such as precipitation and solar radiation, can then be combined with detailed spatial data on topography (e.g. elevation and slope) and soil characteristics (e.g. composition, structure, texture and organic matter) to simulate water availability and the potential biophysical suitability for crop production under future climate change, using gridded crop growth models such as LPJmL (Schaphoff et al., 2018).

Projections on global socio-economic changes can be obtained with computable general equilibrium (CGE) models such as MAGNET, that are able to simulate all sectors of the economy (agriculture, manufacturing and services) across all regions and major countries in the world. CGE models take into account the domestic consumption and supply of production factors (e.g. labour, capital, land, natural resources and use of intermediate inputs across sectors) of the different regions, as well as imports and exports across regions, while accounting for trade barriers via tariffs (Woltjer and Kuiper, 2014; for a review and intercomparison of global economic models see for example Ahammad et al., 2015). Prices of goods, land, labour and capital in each region adjust to ensure that both domestic and international demand and supply are equal. For example, when a policy scenario is simulated to analyse the impacts of lowering tariffs between regions, the model computes consumption and trade by sector, as well as the price levels that ensure equilibrium in domestic and international markets – hence the term 'general equilibrium model'.

The simulation results obtained with CGE models allow regional projections of agroeconomic factors to be derived that, in combination with local biophysical suitability, determine the local utility of agricultural production, specifically the market prices and production costs of different agricultural commodities, and the overall productivity of the related agricultural sectors. In addition, CGE models such as MAGNET incorporate a land supply module that uses a land supply curve to describe a relationship between average real agricultural land rent and the area of land in a region that is used for agriculture (Woltjer and Kuiper, 2014). This module allows future trends of regional land demand to be derived, i.e. the amount of land area that is required to accommodate the expected levels of domestic production, taking into account regional projections on sector productivity and the production volume of agricultural commodities (i.e. the physical quantity that is domestically produced).

Finally, the MagnetGrid land-use model combines the inputs from gridded crop growth models and agroeconomic models to simulate the future spatial patterns of agricultural land use. Firstly, it performs spatial cost–benefit analysis in order to determine the local utility of competing alternatives for agricultural production. According to this assessment, MagnetGrid then applies an economics-based spatial land-use model, with an allocation algorithm that mimics iterative bidding processes on the land market. This algorithm dynamically simulates the allocation of land for different agricultural sectors within a region, by simultaneously fulfilling the regional demand for land in the various sectors and maximising the overall local utility of agricultural land use, while taking land-use patterns in a reference year as a starting point. The spatial land-use model applied in MagnetGrid and the related allocation algorithm are described in more detail in Sections 4 and 5, respectively. The method for the spatially explicit valuation of local utility is outlined in Section 6.

The model simulations obtained with MagnetGrid allow map projections of the future spatial patterns of agricultural land-use change to be derived that can be expected in a region as a result of local economic decisions on the use of land. The model can be run for all the regions of the world, so the regional results for each time step can be aggregated into a single global map of agricultural land use. The MagnetGrid multimodel framework is thus able to provide assessments of the global and regional agricultural land-use change trends that can be expected as the combined result of the interplay between global developments, regional contexts and local land management decisions.

4 Spatial land-use model

As discussed in Sections 2 and 3, MagnetGrid applies a spatial land-use model based on the combination of McFadden's discrete choice theory and Alonso's bid rent theory of land use. For each endogenous land-use type representing a group of actors belonging to a specific sector, we express their willingness to buy/rent land in a location as a bid price map. These bid price maps are generated by valuing the expected local utility that can be expected for each land-use type in a location, given a combination of proximate and underlying factors affecting their local economic performance (the method for valuing local utility is described in Section 6). The choices made by actors between mutually exclusive land-use alternatives is then simulated through a logit-type approach based on McFadden's discrete choice theory. When applied to land-use modelling, the discrete choice model explains the probability of a certain land use being chosen in a particular location, according to the utility of that specific land use in relation to the total utility of all possible alternative land-use types in that location. The discrete choice model can thus be formulated in a spatially explicit way, as a follows (Hilferink and Rietveld, 1999; Diogo et al., 2015; Koomen et al., 2015):

$$X_{c,j} = \frac{e^{\beta . U_{c,j}}}{\sum_{k=1}^{J} e^{\beta . U_{c,k}}} \qquad \text{Eq. (1)}$$

where:

$X_{c,j}$ is the probability of endogenous land-use type j being chosen in gridcell c;
$U_{c,j}$ is the local utility associated with endogenous land-use type j in gridcell c (e.g. in $/hectare);
$U_{c,k}$ is the local utility associated with endogenous land-use type k in gridcell c;
J is a finite number of mutually exclusive endogenous land-use types k, including land-use type j;
β is a parameter to adjust the model sensitivity (1 as default; when β is zero, all endogenous land-use types have the same probability; when β goes to infinity, the probability of the category with the highest suitability is equal to 1).

In the simplest version of the spatial model, the area that is used by each land-use type in each land unit would be obtained as follows:

$$M_{c,j} = A_c \,.\, X_{c,j} \text{ , for all endogenous land-use types } j \text{ and gridcells } c \qquad \text{Eq. (2)}$$

where:

$M_{c,j}$ is the land area used by endogenous land-use type j in gridcell c;
A_c is the area of gridcell c (e.g. in hectare or km^2);
$X_{c,j}$ is the probability of endogenous land-use type j being chosen in gridcell c.

However, the model formulated in Eq. (2) does not guarantee that the allocation of land across land-use types within a region is in accordance with the regional land demand projections. Furthermore, it also does not take into account that some land units may be (partially) occupied by exogenous land-use types for which the conversion to agricultural land use is not deemed feasible (e.g. urban area, water bodies) or desirable (e.g. nature protection area). Therefore, side constraints have to be imposed in order to ensure that total land claims are met at the relevant levels of aggregation, and that the sum of the area of the various land-use types per gridcell (both endogenous and exogenous) is equal to the total area of each gridcell.

This leads to the reformulation of the model as a doubly-constrained logit model (Hilferink and Rietveld, 1999), as follows:

$M_{c,j} = a_j \, . \, b_c \, . \, e^{\beta . U_{c,j}}$, for all endogenous land-use types j and gridcells c Eq. (3)

where:

$M_{c,j}$ is the area of endogenous land-use type j in gridcell c;

a_j and b_c are balancing factors specific to endogenous land-use type j and gridcell c, respectively, so that the constraints specified below in Eqs. 4 and 5 are satisfied.

$\sum_{c=1}^{C} M_{c,j} = D_j$, for all endogenous land-use types j Eq. (4)

$\sum_{j=1}^{J} M_{c,j} = A_c - \sum_{e=1}^{E} M_{c,e}$, for all gridcells c Eq. (5)

where:

$M_{c,j}$ is the area of endogenous land-use type j in gridcell c;

C is total number of allocable gridcells c within the simulated region;

D_j is the total aggregated land claims for endogenous land-use type j, e.g. as projected by MAGNET (e.g. in hectares);

$M_{c,e}$ is the area of exogenous land use e in gridcell c;

J is the total number of endogenous land-use types j;

E is the total number of exogenous land-use types e.

a_j can be interpreted as the demand balancing factor that ensures the total amount of allocated land for the endogenous land-use type j equals the sector-specific land demand. b_c is the supply balancing factor that ensures the total amount of allocated land in cell c does not exceed the amount of land that is available in that particular cell. Solving the model thus entails finding the sets of values for all a_j and b_c that are equal to:

$a_j = \frac{D_j}{\sum_{c=1}^{C} b_c \, . \, e^{\beta . U_{c,j}}}$ Eq. (6)

$b_c = \frac{A_c - \sum_{e=1}^{E} M_{c,e}}{\sum_{j=1}^{J} a_j \, . \, e^{\beta . U_{c,j}}}$ Eq. (7)

The appropriate values for a_j and b_c are found through an iterative approach simulating a bidding process between competing land uses (as described in more detail in Section 5), in which each use will try to get its total demand satisfied, but may be outbid by another land use that derives higher net benefits from land. In a simplified way, the model thus mimics the land market clearing process as outlined in Alonso's bid rent theory of land use (Hilferink and Rietveld, 1999).

5 Spatial allocation algorithm

The doubly-constrained logit model described in Section 4 is solved in MagnetGrid through an iterative proportional fitting procedure, which gradually finds the sets of values for a_j and b_c in Eqs. 6 and 7 that satisfy the constraints outlined in Eqs. 4 and 5, simultaneously for all endogenous land-use types j and for all gridcells c, respectively. This procedure is algebraically described below, in Eqs. 8 to 20; for a more detailed account on the method, we refer to Hilferink and Rietveld (1999). The iterative procedure starts by attributing an arbitrary value 1 for each of the a_j (iteration $i = 0$, in Eq. 8):

$a_{j,i} = \begin{cases} 1, & i = 0 \\ a'_{j,i-1}, & i \geq 1 \end{cases}$, for all endogenous land-use types j Eq. (8)

Eqs. 9 to 11 allow the computation of the resulting values for $b_{c,i}$ in all gridcells c in Eq. 12, as follows:

$T_{c,j,i} = a_{j,i} \, . \, e^{\beta . U_{c,j}}$, for all endogenous land-use types j and gridcells c Eq. (9)

where:

$U_{c,j}$ is the local utility associated with endogenous land-use type j in gridcell c;

β is a parameter to adjust the model sensitivity.

$T_{c,i} = \sum_{j=1}^{J} T_{c,j,i}$, for all gridcells c Eq. (10)

where:

J is the total number of endogenous land-use types j.

$L_c = A_c - \sum_{e=1}^{E} M_{c,e}$, for all gridcells c Eq. (11)

where:

L_c is the land area that is available for allocation of endogenous land uses in gridcell c;

$M_{c,e}$ is the area of exogenous land use e in gridcell c;

E is the total number of exogenous land-use types e.

$b_{c,i} = \frac{L_c}{T_{c,i}}$, for all gridcells c Eq. (12)

Then, Eqs. 13 to 18 allow verification in Eq. 19 of the extent to which the total aggregated land area that is allocated to each endogenous land-use type ($T_{j,i}$) deviates from the respective projected land claims (D_j):

$M_{c,j,i} = b_{c,i} \, . \, T_{c,j,i}$, for all endogenous land-use types j and gridcells c Eq. (13)

$T_{j,i} = \sum_{c=1}^{C} M_{c,j,i}$, for all endogenous land-use types j Eq. (14)

where:

$M_{c,j,i}$ is the area of endogenous land-use type j in gridcell c;

C is total number of allocable gridcells c within the simulated region.

$\delta_{j,i} = T_{j,i} - D_j$, for all endogenous land-use types j Eq. (15)

where:

D_j is the total land claims of endogenous land-use type j (e.g in hectares).

$$\delta_i = \sqrt{\sum_{j=1}^{J} \delta_{j,i}^2} \qquad \text{Eq. (16)}$$

$$D = \sum_{j=1}^{J} D_j \qquad \text{Eq. (17)}$$

$$\tau = \rho \, . \, D \qquad \text{Eq. (18)}$$

where:

ρ is a parameter specifying the share of total aggregated land claims that the allocation model is allowed to deviate from (1% in the current MagnetGrid configuration).

$$S_i = \begin{cases} 0, & \delta_i > \tau \\ 1, & \delta_i \leq \tau \end{cases} \qquad \text{Eq. (19)}$$

If the total deviation is within the prescribed limit, the iteration stops; if not, a_j is recomputed (Eq. 20); this value is then used to start the next iteration in Eq. 8:

$$a'_{j,i} = \begin{cases} a_{j,i} \, . \, \frac{D_j}{T_{j,i}}, & S_i = 0 \\ \textit{iteration stops}, & S_i = 1 \end{cases} \text{, for all endogenous land-use types } j \qquad \text{Eq. (20)}$$

Once the iteration procedure stops at an iteration i for which the total deviation is within an acceptable limit (i.e. $S_i = 1$, in Eq. 19), the area of gridcell c that is used by each endogenous land-use type j is given by $M_{c,j,i}$ (in Eq. 13).

6 Valuation of local utility

In this section, we describe the method that is currently implemented in MagnetGrid for the spatially explicit valuation of local utility of agricultural land use. The approach presented here has been specifically developed to make use of scenario-based agroeconomic projections as simulated by MAGNET.

Agricultural production can be considered as an economic enterprise with a long-term time horizon. For instance, if the price of a certain commodity falls, farmers will wait a few years instead of immediately changing their cropping system, depending on the investments made (Verburg et al., 2002). Therefore, we apply the net present value (NPV), a standard method used in capital budgeting for appraising long-term projects, to assess the potential local economic performance of competing agricultural land uses. The NPV method measures the discounted time series of expected cash inflows and outflows, while taking into account the time value of money (see Section 6.1). According to the NPV method, an investment should have strictly non-negative NPV in order to be regarded as economically viable. The NPV method has already proved suitable for spatially explicit assessments of the economic performance of competing agricultural land uses (see for example Van der Hilst et al., 2010; Kuhlman et al., 2013; Diogo et al., 2015, 2018; Andrée et al., 2017).

Empirical studies have shown that farmers engaged in commercial agriculture do not always convert land to the most profitable production option, partly because they are risk averse, they have to deal with many uncertain factors and might have to incur investments with high sunk costs (see for example Isik and Yang, 2004; Plantinga et al., 2002; Schatzki, 2003; Song et al., 2011; Regan et al., 2015). These factors have appeared to largely explain the inertia of land use and path dependency observed in agricultural land systems (Diogo et al., 2015). Therefore, for the specification of local utility of agricultural land use, we account not only for the potential local economic performance measured in NPV, but also for eventual sunk costs and opportunity costs that are location-specific and depend on previous land-use patterns, being local utility calculated as follows:

$$U_{c,j,t} = NPV_{c,j,t} - SC_{c,j,t} - OC_{c,j,t} \qquad \text{Eq. (21)}$$

where:

$U_{c,j,t}$ is the local utility of agricultural land use *j* in gridcell *c* (in USD$/ha);

$NPV_{c,j,t}$ is the average net present value per unit of land area (in USD$/ha) of agricultural land use *j* in gridcell *c* in time-step *t*;

$SC_{c,j,t}$ is the average sunk costs per unit of land area (in USD$/ha) associated with agricultural land use *j* in gridcell *c*, in time-step t;

$OC_{c,j,t}$ is the average opportunity costs per unit of land area (in USD$/ha) associated with agricultural land use *j* in gridcell *c*, in time-step t.

The definition and spatially explicit specification of these three utility components is described in more detail in the subsections below.

6.1 Net present value

The NPV of a particular land use in a given gridcell is defined as the average local economic performance per unit of land area that could be potentially achieved, should all the land within the gridcell be converted to that land use. Higher NPVs contribute to a higher local utility, so the probability of having land allocated in that gridcell will also be higher compared to a gridcell with a lower NPV, *ceteris paribus*.

When applying the NPV method in a spatially explicit way to agricultural land-use decision-making, NPV can be determined in the following way (adapted from Van der Hilst, 2010):

$$NPV_{c,j,t} = -Inv_{c,j,t} + \sum_{y=1}^{n} \frac{B_{c,j,y} - PC_{c,j,y} + NST_{c,j,t}}{(1+r)^{y}} = -Inv_{c,j,t} + \frac{B_{c,j,t} - PC_{c,j,t} + NST_{c,j,t}}{\frac{r.(1+r)^{n}}{(1+r)^{n}-1}} \qquad \text{Eq. (22)}$$

where:

$Inv_{c,j,t}$ is the average investment costs per unit of land area (in USD$/ha) to convert land in gridcell *c* into agricultural land use j, in time-step t;

$B_{c,j,t}$ is the average annual gross revenues per unit of land area (in USD$/ha) of agricultural land use j in gridcell *c*, in time-step t;

$PC_{c,j,t}$ is the average annual production costs per unit of land area of agricultural land use j in gridcell c (in USD$/ha), in time-step t;

$NST_{c,j,t}$ is the net subsidies and taxes per unit of land area (in USD$/ha) related to agricultural land use j in gridcell *c*, in time-step t;

$\frac{r.(1+r)^{n}}{(1+r)^{n}-1}$ is the capital recovery factor, i.e. the ratio of a constant annuity to the present value of receiving that annuity for a given length of time;

r is the discount rate;

n is the lifetime of the project (in years).

The specification of gross revenues, production costs, net subsidies and taxes, and investments costs is described in Sections 6.1.1 to 6.1.4, respectively.

6.1.1 Gross revenues

Gross revenues are assumed to be obtained from selling commodities in agricultural markets, thus are dependent on market prices and locally attainable productivity. In turn, two important components of local productivity are distinguished, specifically 1) the potential biophysical suitability resulting from a combination of spatial factors setting the agroecological endowments and constraints to grow crops, and 2) the combination of production factors in use (i.e. capital, labour and intermediate inputs). Average annual gross revenues are thus calculated as follows:

$$B_{c,j,t} = S_{c,j,t} \,.\, Y_{R,j,t} \,.\, P_{R,j,t} \,, \; c \in R \qquad \text{Eq. (23)}$$

where:

$S_{c,j,t}$ is the local suitability index of the sector associated with agricultural land use *j* in gridcell *c* (ranging from 0% to 100%, with 100% being optimal local suitability), in time-step *t*. See Section 6.1.1.1. for a description of the method to derive the sectoral suitability maps from crop-specific biophysical suitability maps.

$P_{R,j,t}$ is the market price of commodities produced by agricultural land use *j* in region *R*, in time-step *t* (in USD$/tonne), which in turn is derived from MAGNET scenario projections, as follows:

$$P_{R,j,t} = \frac{TV_{R,j,t}}{TT_{R,j,t}} \qquad \text{Eq. (24)}$$

where:

$TV_{R,j,t}$ is the total production value of the sector related to agricultural land use *j* in region *R* (in USD$), in time-step *t* as projected by MAGNET;

$TT_{R,j,t}$ is the total production volume of the sector related to agricultural land use *j* in region *R* (in tonnes) in region *R*, in time-step *t* as projected by MAGNET;

$Y_{R,j,t}$ is the estimated maximum crop yield/productivity (in tonnes/ha) of the sector related to agricultural land use *j* in region *R*, in time-step *t*. This variable can be interpreted as the yield/productivity levels that can be potentially achieved when the local suitability for that sector is optimal, given a region-specific set of production factors in use by that sector. $Y_{R,j,t}$ is derived from a combination of MAGNET projections, suitability map projections and land use in the previous time-step, as follows:

$$Y_{R,j,t} = \frac{\overline{Y_{R,j,t}}}{\overline{S_{R,j,t}}} \qquad \text{Eq. (25)}$$

where:

$\overline{Y_{R,j,t}}$ is the average yield/productivity of the sector related to agricultural land use *j* in region *R* (in tonnes/ha) in time-step *t*, which in turn is calculated as follows:

$$\overline{Y_{R,j,t}} = \frac{TT_{R,j,t}}{D_{R,j,t}} \qquad \text{Eq. (26)}$$

where:

$TT_{R,j,t}$ is the total production volume of the sector related to agricultural land use *j* in region *R* (in tonnes) in region *R*, in time-step *t* as projected by MAGNET;

$D_{R,j,t}$ is the total land demand of the sector related to agricultural land use *j* in region *R* (in ha), in time-step *t* as projected by MAGNET.

$\overline{S_{R,j,t}}$ is the average local suitability of the sector related to agricultural land use *j* in region *R* in time-step *t*, which in turn is calculated as follows:

$$\overline{S_{R,j,t}} = \frac{\sum_{c=1}^{C}\left(M_{c,j,t-1}\ .\ Suit_{c,j,t}\right)}{\sum_{c=1}^{C} M_{c,j,t-1}}\ ,\ c \in R \qquad \text{Eq. (27)}$$

where:

$M_{c,j,t-1}$ is the area in gridcell *c* that is occupied by agricultural land use *j* (in ha), in the previous time-step *t-1*;

C is the total number of gridcells *c* with land in region *R*.

6.1.1.1 Sectoral suitability maps

The maps representing the local sectoral suitability (i.e. $Suit_{c,j,t}$) are obtained by combining the biophysical suitability index maps of the crops that are part of each sector. Firstly, we derive sector-specific suitability maps for each type of water supply system, i.e. rain-fed systems and irrigated systems. These maps are obtained by attributing to each gridcell the highest suitability value observed in that gridcell from the set of crops that is part of that sector, as follows:

$$S_{c,j,w,t} = \max_{p \in j} S_{c,p,w,t} \qquad \text{Eq. (28)}$$

where:

$S_{c,j,w,t}$ is the sector-specific suitability index of agricultural land use *j* for systems with water supply *w* (i.e. rain-fed or irrigated), in gridcell *c* for time-step *t;*

$S_{c,p,w,t}$ is the crop-specific suitability index of crop *p* for systems with water supply *w*, in gridcell *c* for time-step *t;*

p is a crop that is part of the sector related to agricultural land use *j*.

Finally, the sector-specific maps for rain-fed and irrigated systems are combined into a single map of sector suitability index, according to the spatial distribution of irrigation facilities, as follows:

$$S_{c,j,t} = I_c\ .\ S_{c,j,i,t} + (100\% - I_c)\ .\ S_{c,j,r,t} \qquad \text{Eq. (29)}$$

where:

I_c is the share of total gridcell area in gridcell *c* that is equipped with irrigation facilities (in %, ranging between 0% and 100%);

$S_{c,j,i,t}$ is the sector-specific suitability index of agricultural land use *j* with irrigated systems in gridcell *c*, in time-step *t*;

$S_{c,j,r,t}$ is the sector-specific suitability index of agricultural land use *j* with rain-fed systems in gridcell *c*, in time-step *t*.

The equations outlined above implicitly assume that the most suitable crop types of each sector are representative for their respective sector in terms of overall biophysical suitability in each gridcell. To some extent, this formulation may constitute an oversimplification of sector suitability, since it does not take into account either rotation or competition among crop types of the same sector. This limitation is deemed acceptable for the purpose of simulating global land-use patterns though, as the proposed method allows for a trade-off between data aggregation at the global level and representation of relevant sector characteristics at the local level. In particular, it enables crop suitability data to be handled and combined with global coverage in a consistent and efficient way for sectors that are composed of crop types with highly heterogeneous agroecological requirements. For example, depending on the scenario configuration in MAGNET, the horticultural sector may include both tropical and temperate fruit and vegetables; the sugar crops sector may include both sugar cane and sugar beet; and the oilseeds sector may include disparate crop types such as soybeans, sunflower, rapeseed and palm oil trees. In these cases, aggregation functions such as the mean value would lead to an underestimation of the sector suitability in locations where the agroecological conditions are very suitable for one crop type but unsuitable for another crop type belonging to the same sector. By selecting the highest crop suitability index value in each gridcell, it is then possible to automatically select representative crop types for each sector across different agroecological zones, without having to introduce further assumptions.

6.1.2 Production costs

Production costs include the costs that are incurred due to use of labour and intermediate inputs for agricultural production. MAGNET projections do not distinguish between fixed and variable production costs. Hence, in the current model formulation, production costs are assumed to not depend on the production volume potentially achieved in each gridcell, and therefore they are identical for every gridcell across a region. Average annual production costs are derived from MAGNET projections, as follows:

$$PC_{c,j,t} = \frac{TLC_{R,j,t} + TIC_{R,j,t}}{D_{R,j,t}} \ , \ c \in R \qquad \text{Eq. (30)}$$

where:

$TLC_{R,j,t}$ and $TIC_{R,j,t}$ are the total labour costs and total intermediate input costs of the sector related to agricultural land use j in region R (in USD\$), in time-step t as projected by MAGNET;

$D_{R,j,t}$ is the total land demand of the sector related to agricultural land use j in region R (in ha), in time-step t as projected by MAGNET.

6.1.3 Net subsidies and Taxes

Average net subsidies and taxes are directly derived from MAGNET projections, and are assumed to be dependent on the level of production achieved in each gridcell, as follows:

$$NST_{c,j,t} = \frac{TNST_{R,j,t}}{TT_{R,j,t}} . \ Suit_{c,j,t} \ .Y_{R,j,t} \ , \ c \in R \qquad \text{Eq. (31)}$$

where:

$TNST_{R,j,t}$ is the total net subsidies and taxes (in USD\$) of the sector related to agricultural land use j in region R, in time-step t as projected by MAGNET;

$TT_{R,j,t}$ is the total production volume of the sector related to agricultural land use j in region R (in tonnes) in region R, in time-step t as projected by MAGNET.

6.1.4 Investment costs

Similarly to previous land-use modelling approaches based on economic principles (see for example Diogo et al., 2015; Koomen et al., 2015), farmers are assumed to be specialised in a particular agricultural sector, so that a change of land use involves investment costs for acquisition of land and capital assets (e.g. new buildings, storage facilities and/or machinery) in that location. Hence, investment costs are assumed to be negatively proportional to the area that is occupied in a gridcell by that land use in the previous time-step, since investments are only required to be made on land that is not yet being used for that particular sector. The average investment costs per unit of land area for converting all the available land area in gridcell *c* that is not yet being used by agricultural land use *j* are calculated by taking into account land use in the previous time-step and the use of land by exogenous land-use types, as follows:

$$Inv_{c,j,t} = \frac{A_c - (M_{c,j,t-1} + \sum_{e=1}^{E} M_{c,e,t})}{A_c} \, . \, Inv_{R,j,t} \, , \; c \in R \qquad \text{Eq. (32)}$$

where:

$Inv_{c,j,t}$ is the average investment costs in gridcell *c* for converting the remaining available land area to agricultural use *j* (in USD$/ha), in time-step *t;*

A_c is the total area of gridcell c (e.g. in hectares);

$M_{c,j,t-1}$ is the land area used by agricultural land-use type j in gridcell *c* (e.g. in hectares), in time-step *t-1;*

$\sum_{e=1}^{E} M_{c,e,t}$ is the sum of the land area occupied for all *E* exogenous land uses e (e.g. urban areas and water bodies) in gridcell c (e.g. in hectares), in time-step *t*;

$Inv_{R,j,t}$ is the specific investment costs of agricultural land use *j* per unit of area in region *R* (in USD$/ha) in time-step *t*, which in turn are derived by calculating the present value of the annual land costs and capital costs as derived from MAGNET projections, using a capital recovery factor based on the same time horizon and discount rate assumptions as the NPV, as follows:

$$Inv_{R,j,t} = \frac{\frac{TLaC_{R,j,y} + TCC_{R,j,y}}{D_{R,j,y}}}{\frac{r\,.(1+r)^n}{(1+r)^n - 1}} \qquad \text{Eq. (33)}$$

where $TLaC_{R,j,t}$ and $TCC_{R,j,t}$ are the total land costs and the total capital costs (both in USD$) respectively of the sector related to agricultural land use *j* in region *R*, in time-step *t* as projected by MAGNET;

$D_{R,j,t}$ is the total land demand of the sector related to agricultural land use *j* in region *R* (in hectares), in time-step *t* as projected by MAGNET;

$\frac{r\,.(1+r)^n}{(1+r)^n-1}$ is the capital recovery factor, i.e. the ratio of a constant annuity to the present value of receiving that annuity for a given length of time;

r is the discount rate;

n is the lifetime of the project (in years).

6.2 Sunk costs

The sunk costs associated with the conversion of land to a particular land use in a given location are defined here as the investments for land and capital assets that have already been made in the past in order to put land into production for other land-use types in that same location. Sunk costs aim to capture the potential reluctance of farmers to convert land to a new land use, in cases where the current use has represented a long-term commitment incurring high investment costs. Hence, the average sunk costs that are associated with agricultural land use *j* in gridcell *c* are calculated by measuring the present value of the investment costs of all other agricultural land-use types *k≠j* that were present in that gridcell in the previous time-step, as follows:

$$SC_{c,j,t} = \sum_{k \neq j} \left(\frac{M_{c,k,t-1}}{A_c} \, . \, Inv_{R,k,t} \right) = \sum_{k \neq j} \left(\frac{M_{c,j,t-1}}{A_c} \, . \frac{\frac{TLaC_{R,k,t} + TCC_{R,k,t}}{D_{R,k,t}}}{\frac{r\,.\,(1+r)^n}{(1+r)^n - 1}} \right) \, , \; c \in R \qquad \text{Eq. (34)}$$

where:

$SC_{c,j,t}$ is the average sunk costs associated with converting the available land area in gridcell *c* to agricultural use *j* (in USD$/ha), in time-step *t*;

$M_{c,k,t-1}$ is the land area occupied by agricultural land use *k≠j* in the previous time-step *t-1*;

$Inv_{R,k,t}$ is the specific investment costs of agricultural land use *k≠j* per unit of area in region *R* (in USD$/ha), in time-step *t*;

$D_{R,k,t}$ is the total land demand of the sector related to agricultural land use *k≠j* in region *R* (in hectares), in time-step *t* as projected by MAGNET;

$TLaC_{R,k,t}$ and $TCC_{R,k,t}$ are the total land costs and the total capital costs respectively (both in USD$) of the sector related to agricultural land use *k≠j* in region *R*, in time-step *t* as projected by MAGNET;

$\frac{r.(1+r)^n}{(1+r)^n-1}$ is the capital recovery factor, i.e. the ratio of a constant annuity to the present value of receiving that annuity for a given length of time;

r is the discount rate;

n is the lifetime of the project (in years).

Sunk costs are thus proportional to the area occupied by all the other land-use types in the previous time-step. Sunk costs contribute negatively to the local utility of a land use, so the probability of allocating land to that land use will be lower in a gridcell where a large area was occupied by other agricultural land-use types with high investment costs in the previous time-step, compared to a gridcell where they were absent, *ceteris paribus*.

6.3 Opportunity costs

The opportunity costs associated with the conversion of land to a particular land use are defined here as the net benefits that would be foregone in case all land potentially available for agriculture in a given location were converted to that particular land use. Opportunity costs aim to capture the potential risk aversion of farmers to convert land to a new land use, in cases where the current use already allows them to derive positive net returns. Hence, the average opportunity costs that are associated with a particular agricultural land use *j* in gridcell *c* are calculated by measuring the aggregated discounted net benefits of all other agricultural land-use types $k \neq j$, that were present in that gridcell in the previous time-step, as follows:

$$OC_{c,j,t} = \sum_{k \neq j} \left(\frac{M_{c,k,t-1}}{A_c} \cdot \frac{B_{c,k,t} - PC_{c,k,t} + NST_{c,k,t}}{\frac{r.\,(1+r)^n}{(1+r)^n-1}} \right) \qquad \text{Eq. (35)}$$

where:

$OC_{c,j,t}$ is the average opportunity costs for converting the available land area in gridcell *c* to agricultural use *j* (in USD$/ha), in time-step *t*;

$M_{c,k,t-1}$ is the land area occupied by agricultural land use $k \neq j$ in the previous time-step *t-1*;

$B_{c,k,t}$ is the average gross revenue from agricultural land use $k \neq j$ in gridcell *c* (in USD$/ha), in time-step *t*;

$PC_{c,k,t}$ is the average production costs of agricultural land use $k \neq j$ (in USD$/ha), in time-step *t*;

$NST_{c,k,t}$ is the net subsidies and taxes of the sector related to agricultural land use $k \neq j$ in gridcell *c*, in time-step *t*;

$\frac{r.(1+r)^n}{(1+r)^n-1}$ is the capital recovery factor, i.e. the ratio of a constant annuity to the present value of receiving that annuity for a given length of time;

r is the discount rate;

n is the lifetime of the project (in years).

Similarly to sunk costs, opportunity costs are proportional to the area occupied by the other agricultural land-use types in the previous time-step. They also contribute negatively to the local utility of a land use, so the probability of allocating land to that land use will be lower in a gridcell where high net benefits are already being achieved by other land-use types, compared to a gridcell with low net benefits, *ceteris paribus*.

7 Model workflow and structure

The modelling workflow of the MagnetGrid land-use model involves several steps to coherently integrate data inputs from diverse sources and with different formats, and generate simulation results. In the current model configuration, the following data processing and modelling steps are performed (Fig. 3):

- **Step 1:** Processing and harmonising the spatial datasets with global coverage that are required for the configuration of the model. These datasets represent different aspects of the land system (e.g. agricultural land use, crop biophysical suitability, irrigation infrastructure, urban land use and water bodies), usually obtained from different sources. Section 9 provides an overview of the spatial data requirements for the operationalisation of the model.

- **Step 2:** Combining the crop-specific maps of land use and biophysical suitability, so they are representative of the agricultural sectors that were previously simulated by MAGNET for a given scenario. The crop-specific maps are combined according to tables that describe the relational mapping between crop types and agricultural sectors (see Section 10.1.3). For the land-use maps, the combination is done simply by summing the land area in each gridcell that is used by the different crops that are part of the same agricultural sector; for the suitability maps, the maps of the crops belonging to the same sector are combined by taking the suitability index value from the crop with highest value in each gridcell (see Section 6.1.1.1).

- **Step 3:** Clipping the global spatial datasets (including the sector-specific maps of land use and biophysical suitability generated in task 2, and the exogenous land use maps) in order to create regional maps with the geographic extent of the scenario regions that were simulated by MAGNET. This is done according to tables that describe the relational mapping between administrative regions (e.g. countries) and aggregated regions, as simulated by MAGNET for that particular scenario (see Section 10.1.2). A spatial dataset in shapefile format depicting the administrative boundaries of the original geographic units is used for generating the regional polygon masks that are applied for the spatial clipping of the global datasets.

- **Step 4:** Performing spatially explicit cost–benefit analysis, for valuation of the local utility of each agricultural sector in each simulated region, by combining the regional maps of sectoral suitability and land use with MAGNET regional agroeconomic projections (as described in Section 6).

- **Step 5:** Simulating agriculture land-use patterns in each region according to the spatial allocation algorithm for the optimisation of local utility (as described in Sections 4 and 5), and taking into account the regional land demand for each sector as projected by MAGNET for each time-step. Agricultural land use is dynamically modelled so that the land-use patterns allocated in a given time-step are used as a starting point for the following time-step. Modelling results are exported as regional maps of agricultural land-use patterns for every sector, every region and every time-step specified in a given MAGNET scenario.

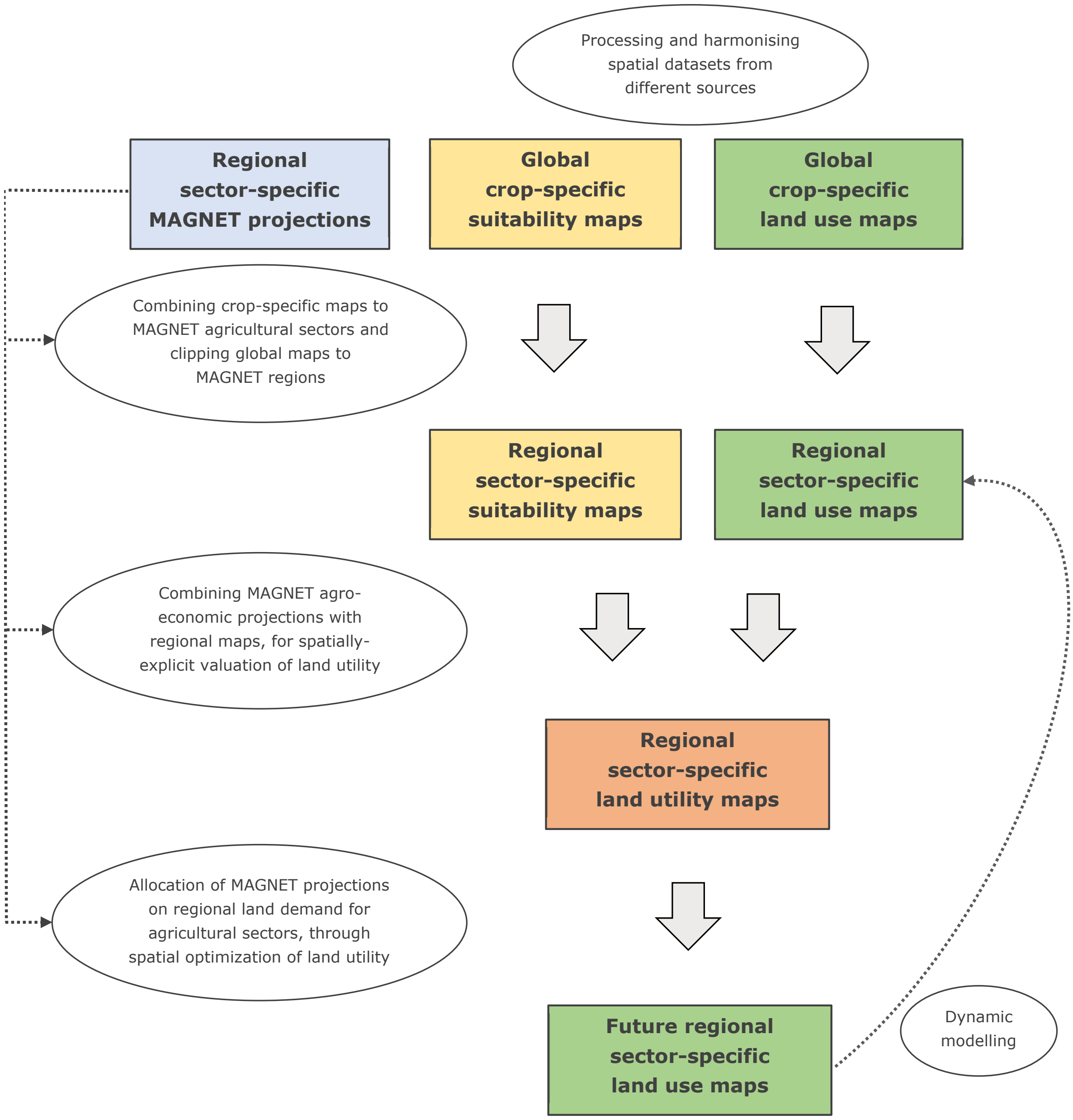

Figure 3 *Modelling workflow of MagnetGrid land-use model*

These modelling steps are performed separately in three dedicated modules:

- **Spatial Data (SD) module**, which performs steps 1 and 2;
- **Spatial Cost–Benefit Analysis (SCBA) module**, which makes use of the global data outputs generated by the SD module, in order to perform step 3 and initialise step 4 (particularly, to generate regional maps of potential NPV for all sectors, as described in Section 6.1);
- **Land-Use Modelling (LUM) module**, which makes use of the regional outputs generated by the SCBA module to first finalise step 4 (more specifically, to combine the NPV maps from the SCBA module with the maps of land-use opportunity costs and sunk costs, that are in turn obtained through spatially explicit assessments that are dynamically dependent on the land-use patterns allocated in the previous time-step, as described in Section 6), and then perform step 5.

To a large extent, many of the modelling units that are simulated by MagnetGrid in a given scenario are defined by the specific configuration of that scenario as previously simulated by MAGNET – for example, the number and composition of simulated agricultural sectors and regions. Hence, the configuration of the three modules is based on templates, so the names of source data files, configuration of modelling units, variables, etc., are not hard-coded in the model code, but instead are specific to a given scenario configuration. This type of modelling approach ensures a high degree of flexibility, so that different scenario alternatives and configurations (e.g. combination of crop types into sectors, aggregation of countries into simulation regions) can be seamlessly and efficiently accommodated in the model. This modular set-up also allows the potential use of MagnetGrid in combination with alternative economic models focused on agricultural land use, other than MAGNET. In Section 10, we describe in more detail the current configuration of the three modules and provide a set of instructions on how to adjust them in order to run a new scenario, as part of the User Guide.

PART II
User guide

8 Software requirements and installation guide

Two software packages are required to operate MagnetGrid modules:

- **R:** A free and open-source software package and programming language that allows a large variety of data formats to be combined for statistical and spatial analysis. R is used in MagnetGrid to run two modules, the *Spatial Data* (SD) and the *Spatial Cost–Benefit Analysis* (SCBA) modules.

- **Geo Data and Model Software (GeoDMS):** A free and open-source software package that is able to process and visualise large (spatial) datasets, and efficiently perform a large array of relatively complex spatial functions such as network analysis and spatial optimisation. GeoDMS has been previously applied in many spatial analysis and land-use modelling tools such as Land Use Scanner and 2UP models (VU Amsterdam, Netherlands Environmental Assessment Agency) and LUISA Territorial Modelling Platform (Joint Research Centre of the European Commission). It is used in MagnetGrid to run the *Land-Use Modelling* (LUM) module. The configuration of GeoDMS modelling applications is specified by writing code in C++ language into text files in .dms format. GeoDMS consists of the following main components (for a detailed account of GeoDMS, we refer to http://www.objectvision.nl/geodms):
  - Model engine component, to control and calculate data, models, model runs, model results and scenarios;
  - GUI component, to view data and metadata in multiple views, and to edit model configurations (see Fig. 4);
  - An executable used to update data items from a command line or batch file.

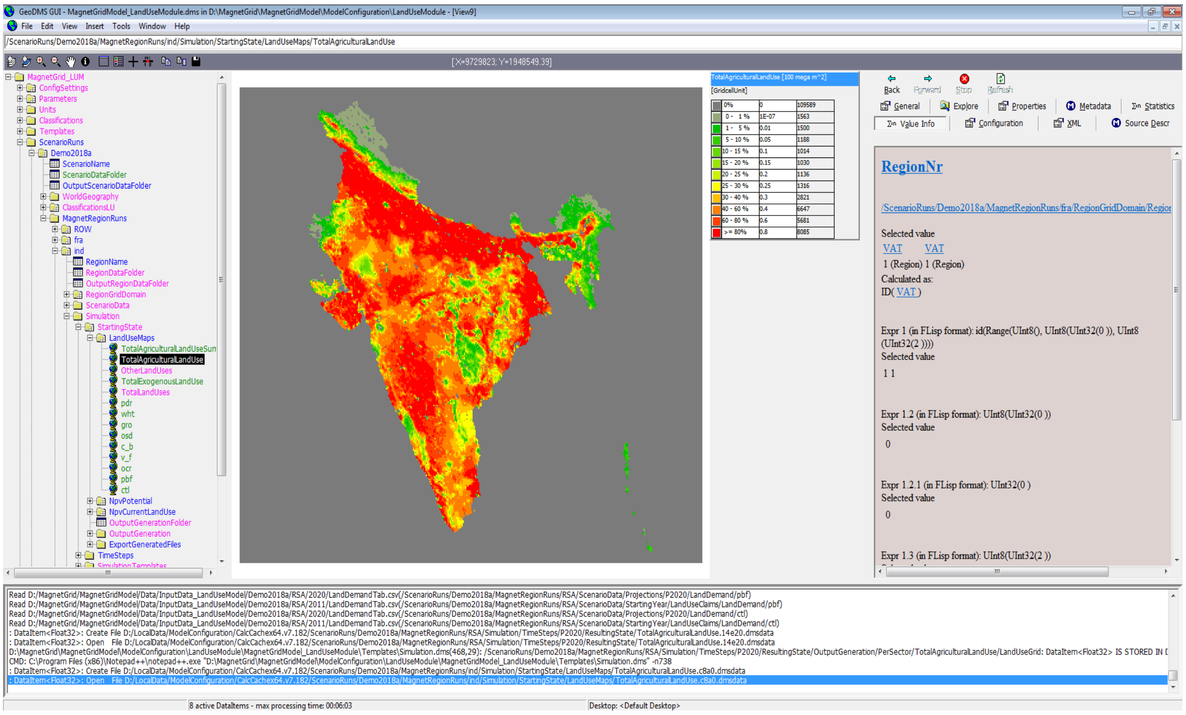

Figure 4 *Example of GeoDMS GUI for the MagnetGrid land-use modelling framework*

In addition, two software packages are suggested as a development environment to edit the code of the different modules:

- **RStudio** – a free and open-source integrated development environment (IDE) for R, which provides a few advantages compared to working on the basic R command line interface such as code completion, retrieving previous commands, viewing and interacting with objects stored in the environment, the ability to interrupt R during a long computation, open, edit and save code, and navigate across different code text files. RStudio can thus be used to configure and run the SD and SCBA modules.

- **Notepad++** – a free and open-source text editor that enables the editing of .dms files. Notepad++ can thus be used to configure the LUM module. In addition, Notepad++ allows language definition schemes to be stipulated, which can provide useful visual feedback on the code, e.g. different colours for different components of the script, such as data items, functions, units, properties, textual notes, etc. (see Fig. 5 for an example).

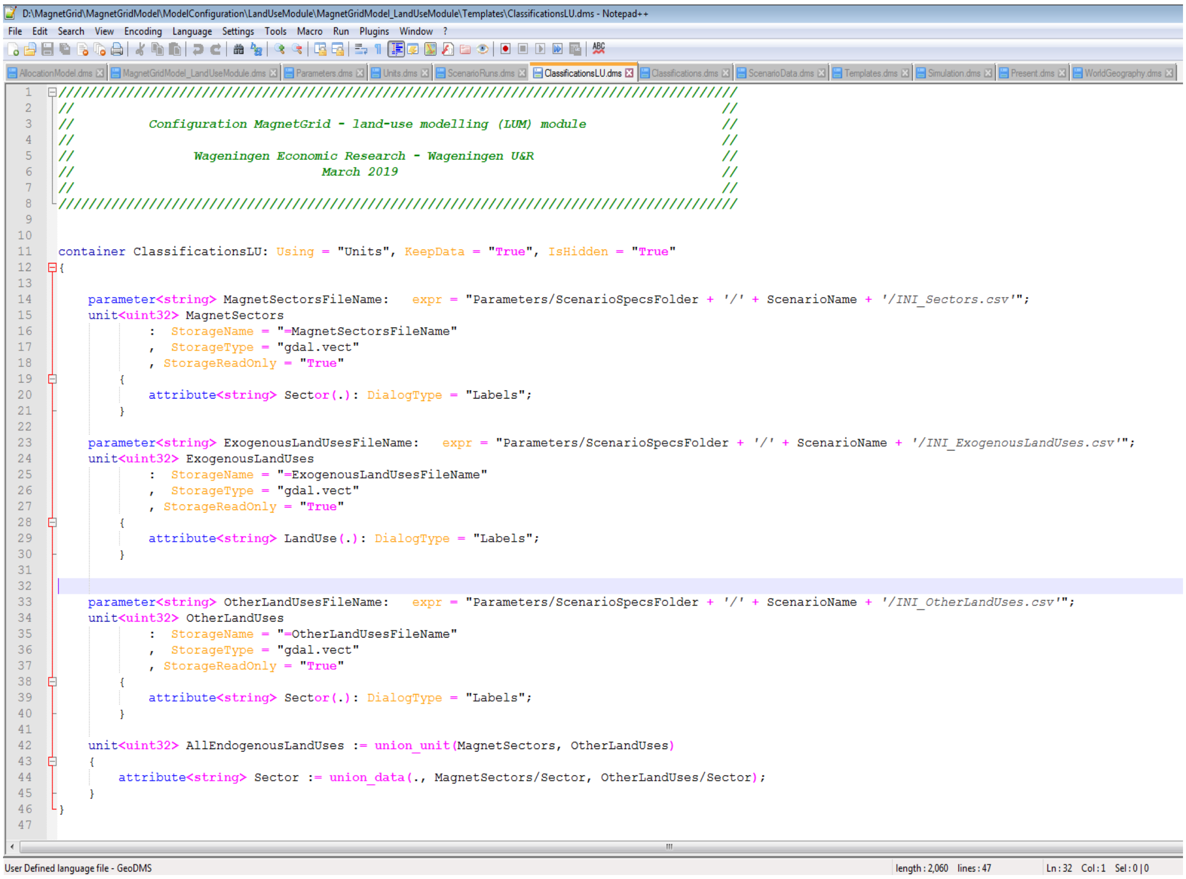

Figure 5 *Example of the language definition colour scheme for .dms files in Notepad++*

These software packages can be installed following the instructions below:

1. Go to the server directory *W:\Projects\MagnetGrid* and copy the file *MagnetGrid.zip* to a local directory (access rights to the server directory may have to be granted prior to accessing the content of the folder – contact Volkert Beekman for more information: volkert.beekman@wur.nl).

2. Unzip *MagnetGrid.zip*. The executable files required to install GeoDMS and Notepad++ software packages can be found in the *Installation* folder[1], as well as the file that is needed to import the language definition scheme for .dms text files in Notepad++ (*GeoDMS_npp_def.xml*).

[1] Alternatively, these executable files can also be downloaded from:
- GeoDMS: http://svn.objectvision.hosting.it-rex.nl/public/geodms/trunk/distr/ (use *guest* as Username and as Password, when requested)
- Notepad++: https://notepad-plus-plus.org/

3. Install GeoDMS with the executable file *GeoDms7182-Setup-x64.exe.*

4. Install Notepad++ text editor with the executable file *npp.7.6.4.Installer.x64.exe.*

5. For changing the colour scheme associated with .dms files in Notepad++, open the Notepad++ executable file by clicking on *Start Menu* -> *Notepad*++ -> *Notepad*++ , then select on the main menu *Language* -> *Define your language* -> *Import*, and select the file *GeoDMS_npp_def.xml* from the *Installation* folder. In the top half of the input box, make sure that the text box reads “dms” (so .dms files are automatically treated as GeoDMS syntax).

6. In case R and/or RStudio software packages are not yet installed, go to the WURClient server application by clicking on *Start Menu* -> *All programs* -> *WUR* -> *!Available Software* and then select the respective software options.

9 Spatial data requirements

Several spatial datasets are required in MagnetGrid to represent different aspects of the land system in MagnetGrid modelling framework, specifically:

- **Crop-specific maps of agricultural land use**, depicting the spatial distribution of different crop types in the starting year of the simulation: These maps should represent land-use area in terms of percentage of gridcell area occupied by a crop, with gridcell values ranging between 0% and 100%. In the current demo version, EarthStat crop land-use maps for the year 2000 (Ramankutty et al., 2008; http://www.earthstat.org/) were used as a data source (see Section 10.2.2). EarthStat data is presented at five minute by five minute spatial resolution in latitude/longitude (approximately 10 km from the equator) in WGS84 projection. The spatial data properties of this dataset were used as a standard to harmonise the remaining spatial datasets in the SD module, since they were identical to other datasets in use, particularly crop suitability and irrigation (see below). Hence, adopting the properties of this dataset as the standard for the SD module means that severe data distortion due to re-projection prior to combining and aggregating crop-specific datasets into sector-specific datasets can be avoided.

- **Time series of crop-specific map projections of biophysical suitability:** These depict the spatial variation of the potential upper limit that is agronomically possible for the production of individual crop types under given agroclimatic, soil and terrain conditions for a specific level of agricultural inputs and management conditions. These maps should represent suitability in terms of percentage indices, with gridcell values ranging between 0% and 100%, 100% being optimal biophysical suitability. These time series should have the same temporal resolution as the simulated scenario time steps from MAGNET projections. In the current demo version, two types of management systems are taken into account, rain-fed and irrigated systems. The IIASA-GAEZ database of potential crop suitability index maps (Fischer et al., 2012; http://gaez.fao.org/Main.html#) was used as a data source, for both rain-fed and irrigated systems (see Section 10.2.3). These datasets are made available with the same spatial resolution and projection as EarthStat, and therefore no data harmonisation operations were necessary.

- **Maps of irrigation infrastructure:** These depict the spatial distribution of agricultural land that is equipped with irrigation facilities. These maps should represent the availability and use of irrigation in terms of percentage of gridcell area that is equipped with irrigation facilities, with gridcell values ranging between 0% and 100%. In the current demo version, FAO-GMIA datasets for 2005 (Siebert et al., 2013; http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm) were used as a data source (see Section 10.2.4). These datasets are made available with the same spatial resolution and projection as EarthStat, and therefore no data harmonisation operations were necessary.

- **Time series of map projections of exogenous land use:** Similarly to crop land use maps, exogenous land-use maps should represent land-use area in terms of percentage of gridcell area occupied by that land-use type, with gridcell values ranging between 0% and 100%. These time series should have the same temporal resolution as the simulated scenario time steps from MAGNET projections. In the current demo version, two types of exogenous land use are considered – urban areas and water bodies (see Section 10.2.5). For urban areas, the GHS-BUILT dataset at 1 km resolution from the Global Human Settlement Layer data series (Pesaresi et al., 2015; https://ghsl.jrc.ec.europa.eu/datasets.php) is used as a data source for depicting the spatial distribution of human settlements and other built-up areas. For water bodies, the ESA-CCI Global Water Bodies dataset at 300 m resolution (Lamarche et al., 2017; https://www.esa-landcover-cci.org/?q=node/162) is used as a data source for depicting the spatial distribution of inland water bodies and oceans. Both datasets were preprocessed in a GIS environment so they could be harmonised with the remaining datasets in terms of spatial resolution, projection and value range.

- **Map of administrative boundaries:** These depict the original geographic regions that will be subsequently aggregated into MAGNET scenario regions in the SCBA module (see Section 10.3). This map should use a projection identical to the one used in the SCBA to export region-specific maps and in the LUM module for the simulation of land-use patterns. Given that land demand projections are given in terms of metric units (e.g. hectare or km^2), an equal area projection should be used in these modules, in order to enable the spatial allocation algorithm to allocate regular geographic units (i.e. gridcells) that are defined in the same units as MAGNET land demand projections. In the current demo version, the SCBA and LUM modules have been configured to operate at a spatial resolution of 10 km (approximately the same resolution in the equator as the original data sources used in the SD module) using the Mollweide projection (see Section 10.3). This projection has been selected for simulating agricultural land use in MagnetGrid, since in previous studies it has demonstrated that it performs best in terms of accuracy for global datasets at spatial resolution levels comparable to those currently used in the model (see for example Usery and Seong, 2000; Jenny et al., 2017). The GADM dataset (https://gadm.org/index.html) is used in the current demo version as a data source for depicting the administrative boundaries of all countries in the world.

10 Running the model

Once the file *MagnetGrid.zip* is unzipped (as described in the installation guide in Section 8), the folder *MagnetGridModel* can be found and a working prototype of MagnetGrid is also available in this folder. The model is organised in the following three folders and respective subfolders:

- The *ModelConfiguration* folder, which contains the configuration code files for the three modules (SD, SCBA and LUM). The following subfolders are included:
  - *SpatialDataAndSpatialCBAmodules*, which contains the R script files with the configuration for the SD and SCBA modules;
  - *LandUseModule*, which contains the .dms script files with the configuration for the LUM module.
- The *SpatialData* folder, which contains the spatial datasets and input data that are required in different modules throughout the modelling workflow, including the following subfolders:
  - *OriginalThematicData*, which contains the original spatial datasets with global coverage that are used for the characterisation of the spatial variables in the model (see Section 9);
  - *RdaFromTiff*, which contains the spatial datasets with global coverage for irrigation, crop land use and crop suitability, after being converted to .rda format by the SD module (see Section 10.2);
  - *ThematicData*, which contains the datasets in .rda format with global coverage for sector land use, sector suitability and exogenous land use after being processed by the SD module (see Section 10.2), and which are then used in SCBA module;
  - *InputData_LandUseModel*, which contains all data inputs required to run the LUM module (e.g. regional maps with NPV projections and land use in the starting year, regional projections of land demand, etc.), as processed by the SCBA module (see Section 10.3).
- The *ScenarioSpecs* folder, which contains the initialisation files that are required for the specification of scenarios and respective modelling units (see Section 10.1).

The provided demo version of the model is fully operational, and is meant to be used as a practice tool for understanding the workflow of MagnetGrid, to become acquainted with its modules and learn how to operate them. In addition, it can also serve as a basis for configuring new scenarios and/or developing new modelling applications. This section provides a set of detailed instructions on how to run the different modules of MagnetGrid, and also how to make adjustments to the model so that new scenario alternatives can be simulated. Firstly, we describe how to set up the initialisation files for the configuration of a scenario (Section 10.1). In Sections 10.2 to 10.4, we describe how to operate and adjust the SD, SCBA and LUM modules, respectively, so that the modelling workflow described in Section 7 can be applied for a particular scenario simulation.

10.1 Setting up the scenario configuration

Prior to running a scenario simulation, the base modelling units in MagnetGrid need to be specified for that scenario, according to the same scenario specification that has been previously simulated by MAGNET. This is done through a set of .csv files that have a function similar to so-called INI files, i.e. text files that are used to set parameters for initialising operating systems and programs. These files are stored within the folder *ScenarioSpecs*.

For specifying a new scenario, the first action is to create a new subfolder within the *ScenarioSpecs* folder, with the name of the scenario. This scenario name will be used throughout the different modules to make reference to where the subfolders with specific data inputs for that scenario can be found/saved throughout the different steps of the modelling workflow. Each scenario-specific subfolder within *ScenarioSpecs* must then include a set of INI files that defines the configuration of the modelling units in MagnetGrid for that scenario, specifically: the different types of land use that are considered as part of the land system (Section 10.1.1); the configuration of the scenario regions in terms of aggregation of the original geographic units (Section 10.1.2); the configuration of the agricultural sectors in terms of crop/commodity aggregation (Section 10.1.3); the time steps that are simulated in the scenario (Section 10.1.4); and the variables and parameters that are considered for the valuation of local utility of agricultural land use (Section 10.1.5). Furthermore, a file with the respective MAGNET scenario projections is also included in the same scenario-specific folder (Section 10.1.6). Hence, in order to successfully run a scenario simulation, it is necessary to first ensure that the names of the modelling units and variables specified in Sections 10.1.1 to 10.1.5 are in accordance with the MAGNET projections for that particular scenario, as specified in Section 10.1.6. In the following sections, a description of the INI files is provided, as well as a set of instructions on how to adjust them for running a new scenario.

10.1.1 Land-use types

INI_Sectors.csv
This table lists the agricultural sectors that are simulated as endogenous land-use types in MagnetGrid and that have been previously simulated in MAGNET for that specific scenario. Two columns are specified:

- *Sector,* which lists the three-letter code of each agricultural sector as simulated in MAGNET for that scenario (e.g. *v_f* for vegetables and fruit).
- *Select,* which indicates the agricultural sectors that are going to be simulated as endogenous land-use types in MagnetGrid (insert *1* for selecting a land use).

INI_ExogenousLandUses.csv
This table lists the exogenous land-use types that are taken into account in the scenario simulation. Exogenous land uses are those that are considered to be spatial constraints for the expansion of agricultural land use. The spatial patterns of exogenous land-use types are not simulated by the model; instead, they have to be provided through external data inputs. Hence, a new exogenous land-use type can only be incorporated in the model as long as a spatial dataset with the appropriate geographic extent (i.e. covering the area that will be later simulated) and temporal resolution (i.e. one dataset for each of the simulated time steps) is available to represent it in the model (see Section 9). Two columns are specified:

- *LandUse*, which lists the name of the exogenous land-use types, as they will be referred throughout the modelling workflow in the three modules;
- *Select,* which indicates the exogenous land-use types that are going to be taken into account in the scenario simulation (insert *1* for selecting a land use).

In the provided demo version, urban/built-up areas and water bodies have been included (referred as *Urban* and *Water*, respectively). In order to add additional exogenous land uses, insert the name of the land use in the column *LandUse*, under the existing ones. Also insert *1* in the column *Select* in the respective line, so the land-use type is included in the model.

INI_OtherLandUses.csv
This table lists the land-use types that are passively simulated, i.e. land-use types that are allowed to be converted for agriculture and for which no specific land claims are defined (for example, (semi-)natural vegetation, barren land, etc.). Two columns are specified:

- *LandUse*, which lists the name of the passive land-use types, as they will be referred to throughout the modelling workflow in the three modules;
- *Select,* which indicates the passive land-use types that are going to be simulated (insert *1* for selecting a land use).

In the current demo version, we do not distinguish different passive land-use types; instead, we define one single land-use type (denoted as *OtherLandUses*) which corresponds to all land that has not been allocated either to endogenous or exogenous land-use types in the previous time step, and that is hypothetically available for allocating agricultural land use in a given time step.

10.1.2 Regions

INI_LinkTableOriginalAdmnRegToMAGNET.csv
This table defines the relational mapping between the original geographic regions, as represented in an administrative boundary map, and the original baseline regions as represented in MAGNET-GTAP

database. In the current demo version, the relational mapping defines the link between all countries of the world (represented with a world map of country boundaries with their respective ISO 3166 alpha-3 country code) to the respective baseline regions in MAGNET-GTAP (e.g. usually countries, but some states may also be aggregated into wider regions, e.g. Fiji and Samoa are part of *Rest of Oceania* baseline region in MAGNET-GTAP). Four columns are specified:

- *ISO3ID*, which lists the ID numerical code of the original administrative units;
- *ISO3*, which lists the respective code (e.g. the ISO 3166 alpha-3 country code) of the original administrative units (e.g. *BRA* for Brazil, *FJI* for Fiji, *WSM* for Samoa);
- *Countryname*, which lists the full name of the original administrative units;
- *MAGNETregion*, which lists the three-letter code of the MAGNET-GTAP baseline regions (e.g. *bra* for Brazil; *xoc* for *Rest of Oceania*) to which the original administrative units is assumed to belong;
- *MAGNETregionNm*, which lists the full name of the MAGNET-GTAP baseline regions (e.g. *Brazil* and *Rest of Oceania*).

This file should only be replaced when either or both of the following apply:

- the administrative boundary map with the original geographic regions is updated (e.g. new countries are recognised);
- the configuration of the baseline regions in the MAGNET-GTAP database is changed.

INI_MappingMAGNETtoScenarioRegionsAggr.csv
This table defines the relational mapping between MAGNET-GTAP baseline regions and the aggregated regions as previously simulated by MAGNET for that specific scenario. Five columns are specified:

- *MAGNETregID,* which lists the ID numerical code of each original baseline region;
- *MAGNETregion,* which lists the three-letter ID code of each original baseline region;
- *MAGNETregionNm,* which lists the full name of the original baseline regions;
- *ScenaRegionCode,* which lists the letter code of the aggregated scenario regions to which the original baseline regions are aggregated (e.g. *WAF* for West Africa);
- *Select,* which indicates the regions that are going to be simulated by MagnetGrid (insert *1* for selecting this region for simulation, otherwise *0*). In the current demo version, only four regions are selected: *fra* (France), *WAF* (West Africa), *ind* (India) and *RSA* (Rest of South Asia).

INI_ScenarioAggregationRegions.csv
This table summarises the aggregated regions simulated in MagnetGrid, following the region configuration previously simulated by MAGNET for that specific scenario. Three columns are specified:

- *ScenaRegID,* which lists the ID numerical code of the aggregated scenario regions;
- *ScenaRegionCode*, which lists the letter code of the aggregated scenario regions (e.g. *WAF* for West Africa);
- *ScenaRegionNm*, which lists the name of the aggregated scenario regions.

10.1.3 Sectors

INI_ProductsSectors.csv
This table defines the relational mapping between the original baseline crops/commodities in the MAGNET-GTAP database and the aggregated agricultural sectors, as previously simulated by MAGNET for that specific scenario. Three columns are specified:

- *ProductID*, which lists the ID numerical code of the baseline crops/commodities;
- *Product*, which lists the four-letter code of the baseline crops/commodities (e.g. *WHEA* for wheat, *MAIZ* for maize);
- *Sector*, which lists the three-letter code of each aggregated agricultural sector (e.g. *v_f* for vegetables and fruit).

As discussed in Section 10.1.1, *INI_Sectors.csv* summarises the agricultural sectors that are simulated in MagnetGrid, following the sector configuration previously simulated by MAGNET for that specific scenario, as defined in *INI_ProductsSectors.csv*.

INI_CropLandUseDataToMagnetSector.csv
This file provides a matrix indicating the relational mapping between the crop types of the source data that is used to represent crop land use in the starting year, and the agricultural sectors as simulated by MAGNET. The first column lists the code names of the crop types as used in the file naming convention for that dataset; the first line lists the code names of the MAGNET agricultural sectors as listed in *INI_Sectors.csv*. If a crop type belongs to a sector, *1* should be inserted in the respective cell, otherwise *0*. An example is provided below in Table 1, showing the relational mapping between a few crop types from the EarthStat crop land use dataset and MAGNET sectors.

Table 1 *Example of relational mapping between crop types in EarthStat crop land use dataset and MAGNET agricultural sectors, as specified in the file INI_CropLandUseDataToMagnetSector.csv*

	c_b	ctl	gro	Ocr	osd	pdr	pbf	v_f	wht
Abacá	0	0	0	0	0	0	1	0	0
Agave	0	0	0	0	0	0	1	0	0
Alfalfa	0	1	0	0	0	0	0	0	0
Almond	0	0	0	0	0	0	0	1	0
Aniseed	0	0	0	1	0	0	0	0	0
Apple	0	0	0	0	0	0	0	1	0
Apricot	0	0	0	0	0	0	0	1	0
Areca	0	0	0	1	0	0	0	0	0
Artichoke	0	0	0	0	0	0	0	1	0
Asparagus	0	0	0	0	0	0	0	1	0
Avocado	0	0	0	0	0	0	0	1	0

INI_CropSuitabilityDataToMagnetSector.csv
This file provides a matrix indicating the relational mapping between the crop types of the source data that is used to represent crop biophysical suitability, and the agricultural sectors as simulated by MAGNET. The first column lists the code names of the crop types as used in the file naming convention for that dataset; the first line lists the code names of the MAGNET agricultural sectors as listed in *INI_Sectors.csv*. If a crop type belongs to a sector, *1* should be inserted in the respective cell, otherwise *0*. An example is provided below in Table 2, showing the relational mapping between a few crop types from the IIASA-GAEZ crop biophysical suitability data series and MAGNET sectors.

Table 2 *Example of relational mapping between crop types in the IIASA-GAEZ crop suitability dataset and MAGNET agricultural sectors, as specified in the file INI_CropSuitabilityDataToMagnetSector.csv*

	c_b	ctl	gro	ocr	osd	pdr	pbf	v_f	wht
Alfalfa	0	1	0	0	0	0	0	0	0
Banana	0	0	0	0	0	0	0	1	0
Barley	0	0	1	0	0	0	0	0	0
Buckwheat	0	0	1	0	0	0	0	0	0
Cabbage	0	0	0	0	0	0	0	1	0
Cacao	0	0	0	1	0	0	0	0	0
Carrot	0	0	0	0	0	0	0	1	0
Cassava	0	0	0	0	0	0	0	1	0
Chickpea	0	0	0	0	0	0	0	1	0
Citrus	0	0	0	0	0	0	0	1	0
Coconut	0	0	0	0	0	0	0	1	0
Coffee	0	0	0	1	0	0	0	0	0
Cotton	0	0	0	0	0	0	1	0	0

10.1.4 Time steps

INI_Years.csv
This table lists the time steps for the scenario simulations in MagnetGrid, according to the respective projections previously simulated by MAGNET for that scenario. Two columns are specified:
- *Year*, which lists the considered time steps (e.g. *2011*, *2020*, *2030*, *2040*, *2050*);
- *Select*, which indicates the time steps that are going to be taken into account in the scenario simulation (insert *1* for selecting this variable, otherwise *0*).

10.1.5 Variables and parameters for valuation of local utility

INI_Variables.csv
This table lists the variables that are used in MagnetGrid for the calculation of the different components of local utility (as described in Section 6) in the SCBA module, and for which projections have been previously simulated by MAGNET for that particular scenario. This list has to be consistent with the name of the variables used in the file with MAGNET projections (see Section 10.1.6). Two columns are specified:
- *Variable*, which lists the names of the variables as they are referred to in MagnetGrid (e.g. *LabourVal* for the value of labour costs). If the names of the variables are changed, then adjustments in the SCBA module script file also have to be made in order to make the name of the variables in the script consistent with the name of the variables in the file with MAGNET projections.
- *Select*, which indicates the variables that are going to be taken into account in the calculation of local utility (insert *1* for selecting a time-step, otherwise *0*).

INI_NpvParameters.csv
This table lists parameters that are required for the NPV calculation of agricultural land use (see Eq. 22) in the SCBA module. Two columns are specified:
- *Parameter*, which indicates the name of the parameter to be specified;
- *Value*, which indicates the numerical value of the parameter.

Currently, two parameters are specified: the discount rate (denoted as *NPV_DiscountRate)* and lifetime (denoted as *NPV_Lifetime*, in years). A discount rate of 5.5% and a lifetime of 20 years is assumed, which is line with previous approaches for modelling agricultural land use based on NPV (see for example Kuhlman et al., 2013; Diogo et al., 2014; Diogo et al., 2015). Both discount rate and lifetime are assumed to be the same for all simulated sectors and regions.

10.1.6 MAGNET projections

MAGNET_data.csv
This table provides the scenario projections as simulated by MAGNET, which are then used in the SCBA module for the valuation of the local utility components. Seven columns are specified:
- *GRID_VAR*, which lists the variable name. The variable names referred in this column must be identical to those indicated in the file *INI_Variables.csv*;
- *UNIT*, which lists the unit of the variables value;
- *SCEN*, which lists the name of the scenario;
- *YEAR*, which lists the simulated time steps. MAGNET cannot deal with numerical variable names, so the time steps are listed as *y_´Year´* (e.g. *y_2011*). The time steps referred in this column must be identical to those indicated in the file *INI_Years.csv* (without the prefix *'y_´* on the latter);
- *GRID_SECT*, which lists the code name of the sectors as simulated by MAGNET. The sector codes referred in this column should be identical to those indicated in the file *INI_Sectors.csv*;
- *REG*, which lists the code name of the regions as simulated by MAGNET. The region codes referred in this column should be identical to those indicated in the file *INI_ScenarioAggregationRegions.csv*;
- *Value*, which lists the numerical value for the respective variable, sector, region and time step, as projected by MAGNET for that particular scenario.

10.2 Spatial data module

The SD module processes the original datasets that are used in the model to represent spatially explicit variables (i.e. agricultural land use in the starting year, projections on potential crop suitability, irrigation infrastructure, urban land use and water bodies), so that they can be integrated in MagnetGrid's modelling framework. It does so by performing two main tasks. Firstly, it converts the spatial datasets (usually in .tif format) to .rda format, so that each gridcell can be linked to the administrative unit (e.g. a country or province) to which it belongs. In the current model configuration, each gridcell is linked to an ISO 3166 alpha-3 country code, so they can be later aggregated into the regions simulated by MAGNET, according to the relational mapping defined in Section 10.1.2. After converting these datasets to .rda format, the module then combines and aggregates the crop-specific datasets (e.g. on land use and potential suitability, see Section 6.1.1.1), according to the relational mappings defined in Section 10.1.3, so that that the resulting .rda datasets are representative of the agricultural sectors simulated by MAGNET. These datasets are then ready to be exported and integrated in the SCBA module.

The SD module has been developed in R programming language. This module is operated by running the main script in the file *SpatialDataModule.R*, which can be found in the folder *ModelConfiguration/SpatialDataAndSpatialCBAmodules.* The module uses a function that gives the option to select which specific tasks should be performed (i.e. converting data to .rda format, aggregating crop data into sector data) and for which type of data (i.e. crop land use, crop suitability, exogenous land use). The reason to include these options is that different scenarios may make use of the same baseline data. For example, different policy scenarios may make use of the same crop land use data to represent agricultural land use in the starting year; the same may also apply to urban land use projections. Thus, if only the scenario-specific crop suitability data is to be processed, not the entire set of baseline data, instead copy the common datasets that have already been processed to the respective scenario folders, in order to save computing time and storage space. In addition, the original source data for crop-specific datasets may have already been converted once to .rda format, but distinct definitions of relational mapping for aggregating crops to agricultural sectors may be required for different scenarios. Hence, there is the possibility of aggregating crop-specific data multiple times according to different relational mappings, without always having to first convert the original datasets to .rda format.

Dedicated R script files were created for each combination of task and data type. These files are called upon by the function in the main script, according to the selections made by the user (more detailed information on how to select options for this function can be found below in Section 10.2.6, as part of the set of instructions on how to operate the SD module). The script files for each combination of task and data type can be found in the folder *ModelConfiguration/SpatialDataAndSpatialCBAmodules/SpatialDataModuleScripts*, as follows:

- *LandUseData_RdaFromTiff.R* – converts datasets of crop land use from .tif to .rda format;
- *SuitabilityData_RdaFromTiff.R* – converts datasets of crop suitability from .tif to .rda format;
- *ExogenousLandUseData_RdaFromTiff.R* – converts datasets of exogenous land use (e.g. urban, water) from .tif to .rda format;
- *LandUseData_CombineToMagnet.R* – combines datasets of crop land use into sectoral land-use maps according to the relational mapping defined in the scenario-specific INI file *INI_CropLandUseDataToMagnetSector.csv*;
- *SuitabilityData_CombineToMagnet.R* – combines datasets of crop suitability into sectoral suitability maps (see Section 6.1.1.1) according to the relational mapping defined in *INI_CropSuitabilityDataToMagnetSector.csv*.

In order to operate this module for running a particular scenario, a number of code lines need to be appropriately adjusted in the main script file *SpatialDataModule.R* (e.g. using RStudio as a development environment). Such code lines are identified in the script with the marker *## @USER INPUT*, followed by an instruction on how to adjust the code. These lines are mostly related to specifying the path for data folders and input files, as well as placeholders to export (intermediate) results. A comprehensive list of the code lines that need to be adjusted by the user, and instructions on how to adjust them, is provided below in Sections 10.2.1 to 10.2.6. Note that only the parts of the code that are in bold should be modified.

10.2.1 General instructions

*MagnetGridPath<<-"**D:/MagnetGrid/MagnetGridModel/**"*
Indicate the path for the main root directory of the model, i.e. where the folders *ModelConfiguration*, *SpatialData* and *ScenarioSpecs* are stored.

*Scenarios<- c('**Demo2018a', 'Demo2018b', 'Project1/Demo2019a', 'Project1/Demo2019b**')*
Indicate the names of the scenarios to be run by the module. In this example, four hypothetical scenarios are included for illustrative purposes: *Demo2018a* and *Demo2018b*, with each scenario having its own dedicated subfolder in the *ScenarioSpecs* folder and in addition, two scenarios that are assumed to be part of the same project and are organised in a common project folder, with each scenario then having its own dedicated subfolder. These latter scenarios are referred as *Project1/Demo2019a* and *Project1/Demo2019b*, meaning that a project subfolder named *Project1* is placed in the *ScenarioSpecs* folder, then containing two additional scenario-specific subfolders named *Demo2019a* and *Demo2019b*.

*AdmnRegionsGridcellFile <<- paste(SpatialSourceDataPath, "**CountriesXY.csv**", sep="")*
Indicate the name of the file listing the XY coordinates of every land gridcell and the (ISO) codes of the administrative region (e.g. country or provinces) to which the gridcells belong. Make sure to store this file in the folder *SpatialData/OriginalThematicData*. This file should be prepared by rasterising a shapefile with the original administrative boundaries of the regions indicated in the file *INI_LinkTableOriginalAdmnRegToMAGNET.csv*, with the same projection as the one indicated in *OriginalProj* in the LUM module (see Section 10.3) and with same resolution as the harmonised source data files in *SpatialData/OriginalThematicData*. The file made available in the current demo version has been prepared based on a regular grid of 5′ × 5′ resolution in WGS84 projection, since this is the resolution and projection that was used as a standard for the harmonisation of the global spatial datasets used as a data source. It uses the ISO 3166 alpha-3 country code standard for identifying the countries to which each gridcell belongs. For processing datasets in different resolutions, projections or country/region classification standard, a new file must be prepared.

10.2.2 Crop land use data

*LandUseDataFolder <<- "**EarthStat/**"*
Indicate the name of the folder with the source data for crop land use in the starting year. In the current demo version, EarthStat crop land-use maps are used. This folder should be placed in the directory *SpatialData/OriginalThematicData/CropLandUse*.

*LandUseCropSubfolder = **TRUE***
Indicate whether there is a dedicated subfolder for each crop type: *TRUE* if that is the case, otherwise *FALSE*. In the case of EarthStat data, each crop has a dedicated subfolder.

LandUseSubfolderPrefix<<-""
Adjust according to the naming conventions of the subfolders for the crop land-use datasets. In the case of EarthStat data, there is no prefix in the subfolder name before the crop type, thus double quotation marks with no space in between are inserted here.

*LandUseSubfolderSuffix <<- "**_HarvAreaYield_Geotiff/**"*
Adjust according to the naming conventions of the subfolders for crop land-use datasets. In the case of EarthStat data, every crop has its own dedicated subfolder with a standard suffix after the name of the crop (e.g. *banana_HarvAreaYield_Geotiff* as subfolder name).

LandUseFilePrefix<<-""
Adjust according to the file naming conventions for the crop land-use data. In the case of EarthStat data, there is no prefix in the file name before the name of the crop type.

*LandUseFileSuffix <<- "**_HarvestedAreaFraction.tif**"*
Adjust according to the file naming conventions for the crop land-use data. In the case of EarthStat data, every crop-specific file has a standard suffix after the name of the crop (e.g. *banana_HarvestedAreaFraction.tif* as a file name). Note that the format of the raster file should also be added here (e.g., *.tif)*.

10.2.3 Crop suitability data

For the source data used to represent crop suitability, each scenario should have its dedicated subfolder inside the folder *SpatialData/OriginalThematicData/CropSuitability*, and with the same name as the scenario name indicated above in *Scenarios*. The scenario subfolder should then be followed by subfolders with the same names as the simulation time steps indicated in *Years.csv*, which in turn should have raster files with the crop suitability projections for that time step. In the current demo version, IIASA-GAEZ (Fischer et al., 2012; http://gaez.fao.org/Main.html#) crop suitability index datasets are used, for both rain-fed and irrigated systems, with respect to the baseline period (1961–1990) with high input levels. These datasets are used for every time step, i.e. it is implicitly assumed that there is no change in the crop biophysical suitability. Inside each time-step folder, there are dedicated subfolders with the suitability data for rain-fed and irrigated systems, each with the same name as the technology system indicated below in *SuitabilityTechnologyTypes*.

*SuitabilityTechnologyTypes <<- c(**'Irrigated', 'Rainfed'**)*
Indicate the names of the different types of technology that are taken into account, in respect to the crop suitability data. Note that each technology-specific set of crop suitability datasets must be stored in a dedicated subfolder with the names of the technology given here, for each time step. In the current demo version, only rain-fed and irrigated systems are distinguished, through the use of spatial datasets on irrigation infrastructure (as described in Section 6.1.1.1), that are stored in the folder indicated below in *IrrigationDataFolder*. Adjustments to the *SuitabilityData_CombineToMagnet.R* model script may have to be made in case more types of technology are taken into account.

*SuitabilityCropSubfolder = **FALSE***
Indicate whether there is a subfolder for each crop type: *TRUE* if that is the case, otherwise *FALSE*. In the case of IIASA-GAEZ data, the crop-specific datasets for each type of technology system are stored in the same folder, so no crop subfolder needs to be added.

SuitabilitySubfolderPrefix <<-""
Adjust according to the naming conventions of the subfolders with suitability datasets. In the case of IIASA-GAEZ data, there is no crop-specific subfolder.

SuitabilitySubfolderSuffix <<-""
Adjust according to the naming conventions of the subfolders with suitability datasets. In the case of IIASA-GAEZ data, there is no crop-specific subfolder.

SuitabilityFilePrefix<<-""
Adjust according to file naming conventions for the suitability datasets. In the case of IIASA-GAEZ data, there is no prefix in the file name before the crop type, thus double quotation marks, with no space in between, are inserted.

*SuitabilityFileSuffix <<- "**.tif**"*
Adjust according to the file naming conventions for the crop suitability data. In the case of IIASA-GAEZ data, there is no suffix in the file name after the crop type (i.e. each file is named only after the crop, e.g. *banana.tif*). However, the format of the file still needs to be added, thus *".tif"* has been inserted in this item.

10.2.4 Irrigation data

*IrrigationDataFolder <<- "**Irrigation/**"*
Indicate the name of the folder with the raster files specifying the area equipped with irrigation infrastructure. This folder should be placed in the directory *SpatialData/OriginalThematicData*. In the current demo version, FAO-GMIA datasets are used (Siebert et al., 2013; http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm).

*IrrigationFileNames <<- c('**gmia_v5_aei_pct.asc', 'gmia_v5_aai_pct_aei.asc**')*
Indicate the names of the files specifying the area equipped with irrigation facilities. These files should be stored in the same folder as shown in *IrrigationDataFolder*.

*IrrigationVariables <<- c('**IrrigEquippedArea', 'IrrigAreaActuallyUsed**')*
Indicate the name of the variables for the files specifying the area equipped with irrigation facilities, in the same order as shown in *IrrigationFileNames*.

10.2.5 Exogenous land use data

For the source data that is used to represent exogenous land use, each scenario must have its dedicated subfolder inside the folder *SpatialData/OriginalThematicData/ExogenousLandUses*, with the same name as the scenario name indicated above in *Scenarios*. The scenario subfolder should then be followed by subfolders with the same names as the simulation time steps indicated in *Years.csv*, which in turn should have raster files with the exogenous land-use projections for that time step. The files in each time-step folder should have the same name as the exogenous land-use name indicated in *ExogenousLandUsesLis* (e.g. *Urban.tif*).

*ExogenousLandUsesLis <<- c(**'Urban' ,'Water'**)*
Indicate the names of the exogenous land-use types considered in the simulated scenarios. In the current demo version, the GHS-BUILT dataset is used (Pesaresi et al., 2015; https://ghsl.jrc.ec.europa.eu/data.php) to derive land-cover share datasets for representing urban areas. The ESA-CCI land-cover 2010 layer (Lamarche et al., 2017; https://www.esa-landcover-cci.org/?q=node/158) is used to derive land-cover share datasets for representing water bodies. The same datasets are used for every time step, i.e. it is implicitly assumed that there is no change in the spatial distribution of urban areas and water bodies. Note that if the same datasets are used for different scenarios, they should be converted only once for one scenario, and then copied to the other scenario-specific folders, instead of converting the datasets each time for each scenario.

10.2.6 Spatial data module function

```
SpatialDataModule <- function(
   ConvertData_RdaFromTiff               = TRUE
 , CropLandUseData_RdaFromTiff           = TRUE
 , CropSuitabilityData_RdaFromTiff       = TRUE
 , ExogenousLandUseData_RdaFromTiff      = TRUE

 , CombineCropDataToMagnetSectors        = TRUE
 , CropLandUseData_CombineToMagnet       = TRUE
 , CropSuitabilityData_CombineToMagnet   = TRUE )
```

Indicate here which tasks will be performed by the module and for which types of data: *TRUE* to select the respective option, otherwise *FALSE*. Two of the options precede the others, specifically:

- *ConvertData_RdaFromTiff*, which commands whether any data will be converted from .tif to .rda formats at all. This option has to be selected (i.e. *TRUE*) in order to convert to .rda the following types of data: crop land use, crop suitability and/or exogenous land use. One should then indicate *TRUE* or *FALSE* in each respective line to select which type of data to convert. However, note that if the first option is set as *FALSE*, then none of these data types will be converted, even if its respective option is set as *TRUE*. The datasets generated with these tasks are exported to the folder *SpatialData/RdaFromTif*.

- *CombineCropDataToMagnetSectors*, which commands whether any crop-specific data will be combined and aggregated to MAGNET sectors at all. This option has to be selected (i.e. *TRUE*) in order to combine and aggregate the following types of data: crop land use, and crop suitability. One should then indicate *TRUE* or *FALSE* in each respective line to select which type of data will be combined to MAGNET sectors. However, if the first option is set as *FALSE*, then none of the data types will be combined, even if its respective option is set as *TRUE*. The datasets generated with these tasks are exported to the folder *SpatialData*/*ThematicMaps*.

10.3 Spatial cost–benefit analysis module

The main functions of the SCBA module are to generate regional maps of potential NPV for all agricultural sectors, time steps and regions as previously simulated by MAGNET, and export all the data inputs that are required to subsequently simulate the allocation of agricultural land use in the LUM module. Firstly, it disaggregates the data outputs with global coverage previously generated with the SD module into regional datasets, based on the relational mapping between countries (or other type of administrative boundary) and aggregated regions as defined in the file *INI_MappingMAGNETtoScenarioRegionsAggr.csv*. Then, it combines the resulting regional maps of sectoral suitability with the respective MAGNET regional projections on sector productivity, market prices and production costs, in order to perform NPV valuation of agricultural production in a spatially explicit way for all sectors and time steps in each simulated region. Finally, the module exports to a scenario-specific subfolder in the directory *SpatialData/InputData_LandUseModel* the following datasets, which will be required for the simulation of agricultural land use in the LUM module:

- a global shapefile map with the boundaries of the simulated regions;
- a .csv file for each simulated region, listing the geographical attributes that define the regular grid of the rectangle covering the geographical extent of the region, specifically:
  - the four corner coordinates (i.e. top-left, top-right, bottom-left and bottom-right)
  - number of rows and columns
- a raster map for each simulated region representing the land territory of the region;
- raster maps of sector land use in the starting year of the simulation, for each agricultural sector in each simulated region;
- raster maps of potential NPV (as calculated in Section 6.1) for each agricultural sector, for every time step in each simulated region;
- tables with projections of specific investment costs (as defined in Section 6.1.4) for all the agricultural sectors, for every time step in each simulated region. These projections are meant to be used for the spatially explicit valuation of investment costs and sunk costs (Sections 6.1.4 and 6.2, respectively) within the LUM module;
- tables with projections of land demand for all the agricultural sectors, for every time step in each simulated region.

The SCBA module has been developed in R programming language. This module is operated by running the main script in the file *SpatialCBA_module.R* file, which can be found in the folder *ModelConfiguration/SpatialDataAndSpatialCBAmodules.* For running a particular scenario, only a few adjustments have to be made on the code of the existing R script file (e.g. using RStudio as a development environment). Such code lines are identified with the marker *## @USER INPUT* in the script, followed by an instruction on how to adjust the code. These lines are mostly related to specifying the appropriate path for folders and input files, and the geographic projection and resolution of the spatial datasets exported by the module, as indicated below.

*MagnetGridPath='**D:/MagnetGrid/MagnetGridModel**'*
Indicate the path for the main root directory of the model, i.e. where the three folders *ModelConfiguration*, *SpatialData* and *ScenarioSpecs* are stored.

*Scenarios<- c('**Demo2018a', 'Demo2018b', 'Project1/Demo2019a', 'Project1/Demo2019**b')*
Indicate the name of the scenarios to be run by the module. In the present example, four scenarios are listed. Note that if a scenario is part of an overall project with a common folder (as discussed in Section 10.1), the name of the project folder should be mentioned before the name of the scenario (e.g. as in *Project1/Demo2019a*).

*OriginalProj<- CRS('**+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs**')*
Indicate the original projection of the spatial datasets that were previously processed in the SD module. In the current demo version, these datasets are projected in WGS84.

*LUMproj<- "**+proj=moll**"*
Indicate the projection of the spatial datasets that are exported by the SCBA to be used in the LUM module. In the current demo version, these datasets are re-projected into the Mollweide equal area.

*GridcellSize <- **10000***
Indicate the gridcell resolution (in metres) of the spatial datasets that are exported by the SCBA to be used in the LUM module. In the current demo version, these datasets are re-projected into a regular grid of 10,000 m, i.e. 10 × 10 km gridcell resolution, which is approximately the size of the original 5' × 5' gridcell in the WGS84 projection near the equator.

*OriginalAdmnBoundaries<-shapefile('**SpatialData/WorldMaps/world_map_mollweide.shp**')*
Indicate the file (and respective folder) for the spatial dataset in shapefile format with the boundaries for the original administrative units. This file will be used as a basis to combine and aggregate the original administrative units into the regions simulated by MAGNET. Make sure this shapefile is in the same projection as that indicated above in *LUMproj*. This file should make use of the same codes for the original administrative units as those used in the INI file *INI_LinkTableOriginalAdmnRegToMAGNET.csv* and in the file indicated in *AdmnRegionsGridcellFile*. Therefore, the file referred in *OriginalAdmnBoundaries* should be prepared by re-projecting the shapefile that was used to derive the file indicated in *AdmnRegionsGridcellFile* to the projection indicated in *LUMproj*.

*OriginalAdmnBoundaries@data=OriginalAdmnBoundaries@data[,
c("**OBJECTID","ISO_3DIGIT","CNTRY_NAME","SQKM"**)]*
Indicate the data attributes from the original map with administrative boundaries (mentioned above in *OriginalAdmnBoundaries*) that will be used for the aggregation into MAGNET scenario regions. Make sure to adjust the script of the module functions accordingly, in case the name of these attributes are different than the ones currently indicated.

10.4 Land-use modelling (LUM) module

The main functions of the LUM module are to perform valuation of local utility for the simulated agricultural sectors (as described in Section 6) and accordingly simulate the allocation of land for agricultural land-use types (as described in Section 5), using the data inputs generated by the SCBA module. It projects and exports maps of land-use share per gridcell for each combination of simulated agricultural sector, time step and region.

The LUM module has been developed in C++ programming language and should be operated using GeoDMS GUI. The .dms script files with the code for the LUM module can be found in the folder *ModelConfiguration/LandUseModule.* This module is relatively more complex to operate than the SD and SCBA modules, using a large number of templates for accommodating different scenario configurations and respective modelling units. Therefore, apart from simpler actions such as changing model parameters, its configuration should be adjusted only by experienced GeoDMS users. In this section we provide a set of instructions on how to operate the LUM module for users with no previous experience with GeoDMS.

10.4.1 Setting up the GeoDMS modelling environment

For starting GeoDMS GUI, go to *Starting Menu -> All Programs -> GeoDMS -> version7182* and click on the icon *GeoDms Gui 7182-x64* (for faster access, we suggest creating a shortcut to this item on the desktop environment). When starting the GUI, a configuration file in .dms format needs to be opened. Open the file *MagnetGridModel_LandUseModule.dms*, available in the folder *ModelConfiguration/LandUseModule*. On opening this file, a number of options need to be specified. Go to *Tools -> Options* on the main menu of the GUI. Go to the *General Settings* tab and adjust the following options (see Fig. 6):

- ***DMS editor***: GeoDMS GUI allows direct access to default .dms file editor software (e.g. Notepad++) in order to adjust the module data items (e.g. by giving the shortcut command *Control+E* on the tree item respective to the data item that needs to be adjusted). Insert the path for the executable file of the text editor of choice here, followed by a set of instructions for opening the respective .dms file on the code line number with the script configuration for the data item that needs to be adjusted. For example:

  C:\Program Files (x86)\Notepad++\notepad++.exe "%F" -n%L

- ***Administrator mode***: The administrator mode allows access to more advanced functionalities and for the full tree structure of data items to be visible on the tree view, including those used for intermediate calculations. However, this may also lead to a more cluttered modelling environment. We advise inexperienced GeoDMS users to unselect the administrator mode, in order to have a cleaner tree view structure and modelling environment, without compromising access to all the functionalities and data items that are needed for running the module.

- ***LocalDataDir***: This is the directory where GeoDMS stores (intermediate) calculation results (the so-called *CalcCache* folder) and exports maps with the scenario simulation results. Indicate here the path to the directory for the *LocalDataDir*, for example: *D:\LocalData*. The *CalcCache* should be considered as an extension of the internal memory. Therefore, configuring a network drive for the *CalcCache* folder is discouraged as it will slow down the application and burden the storage space availability in the network. The *CalcCache* folder and subfolders are automatically created by the GeoDMS when the (intermediate) results need to be stored. The *CalCache* folder has a tendency to grow quickly in size, especially when multiple modifications are made to the configuration and the results of these modified items are requested at least once. To keep the size of the *CalcCache* limited, we advise the following.
  - Compress the directory indicated in *LocalDataDir*. This can be done by right-clicking on the folder icon in Windows Explorer, selecting *Properties*, selecting *Advanced* and finally ticking the option *Compress contents to save disk space*. When confirming the attribute changes, select *Apply changes to this folder, subfolders and files*. The folder name will then show up in blue letters on Windows Explorer. An additional disadvantage of configuring the *LocalDataDir* within a network drive is that this option does not allow the content of the folder to be compressed.
  - Delete *CalcCache* folders that are not recently used, frequently. *CalcCache* folders contain files that can always be recalculated. Therefore, *CalcCache* folders (and subfolders) may be deleted without losing relevant data or information. The only disadvantage of deleting a *CalcCache* folder is that it will take more time to recalculate requested results. We advise deleting the *CalcCache* folder every time after running a (number of) scenario(s).

- ***SourceDataDir***: This is the directory with all the data inputs that are required to run the LUM module, i.e. the datasets that were previously generated with the SCBA module. Insert the path to the respective directory here, for example:

  D:\MagnetGrid\MagnetGridModel\SpatialData\InputData_LandUseModel

After adjusting these options, the GeoDMS GUI should be re-initialised in order to activate these settings.

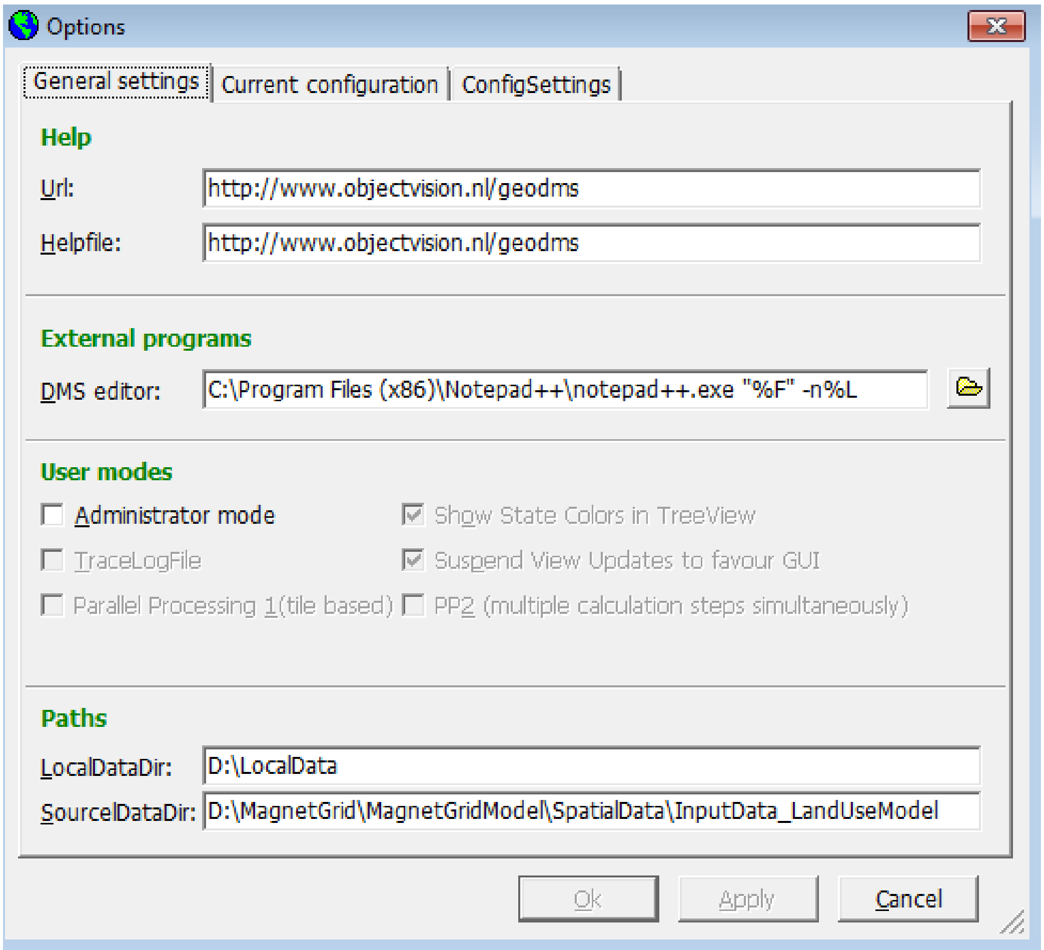

Figure 6 *Example of how to configure the general settings in GeoDMS GUI*

10.4.2 Using the GeoDMS GUI

The GeoDMS GUI allows the calculation and visualisation of different types of data items in the LUM module. Two main elements are part of the GUI (Fig. 7):

- The tree view area, on the left side of the GUI, which allows navigation through the different data items of the module. This tree view uses a hierarchical structure similar to those of folders, subfolders and files in Windows Explorer. In GeoDMS terminology, data items that contain other data items within them (similarly to folders in Windows Explorer) are termed containers.
- The data visualisation area, in the remaining area, which displays the data item that has been double-clicked on the tree view. Spatial data items (which can be identified by a globe icon on the tree view) can be visualised both as maps (with the respective legend on the side) and as tables. The map view is selected by default when double-clicking on the data item; to select the table view, right-click on the data item and then select the required option.

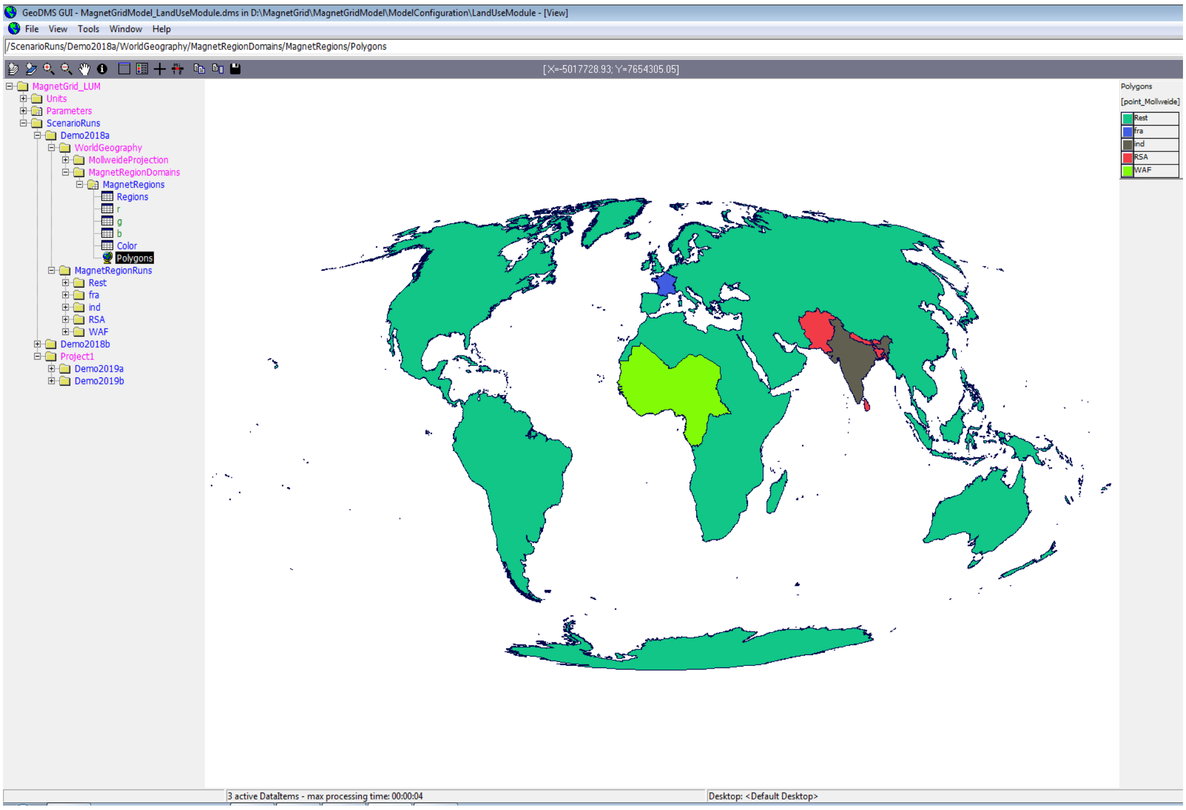

Figure 7 *Using the tree view in the GeoDMS GUI (on the left side) to navigate through the hierarchical structure of the LUM module and visualise data items. In this example, a map showing the geographic units of a scenario is displayed*

The GUI allows the user to not only calculate and immediately visualise (intermediate) modelling results, but also to control for the input data and definition of the modelling units that are used as a basis for the scenario simulations. In the current demo version, three main containers are visible when the *Administrator Mode* is off (see Fig. 7):

- *Units*: In this container, base metric units and derived metric units are defined. Metric units are useful not only to inform how values of data items should be interpreted, but also to check for inconsistencies in calculations. For example, a data item expressed in metres cannot be meaningfully summed with a data item expressed in seconds. This also applies to data items expressed in kilometres, although this item could be summed with the data item expressed in metres if it was first divided by 1,000 metres per kilometre. In this case, it may be useful to define a derived unit (kilometre) from a base metric unit (metre). Hence, for data items defining quantities it is strongly advised to configure expressions for units, resulting in a metric unit.
- *Parameters*: In this container, a number of important parameters and model units are specified. These parameters and units may be specific to a set of scenarios, and therefore they should be specified by the user prior to running the module for those particular scenarios (see Section 10.4.3 for a more detailed account of adjusting the data items in the *Parameters* container).
- *ScenarioRuns:* In this container, all data items related to data inputs and calculations for running a particular scenario are specified. This container is based on a template, which follows a hierarchical structure as described below (see also Fig. 7):
  - Containers with the name of the scenarios (e.g. *Demo2018a, Demo2018b, Project1/Demo2019a*).
    - *WorldGeography*: This container defines the projection (subcontainer *MollweideProjection*) and geographic units for the aggregated regions that will be simulated in that particular scenario (subcontainer *MagnetRegionsDomains*). In Fig 7, an example of a visualisation in the GeoDMS GUI is shown, with the map defining the geographic units for simulation in the demo scenario (i.e. spatial data item *Polygons*, in the *MagnetRegionsDomains/MagnetRegions* subcontainer).
    - *MagnetRegionRuns*: This container includes region-specific subcontainers for each of the regions defined in *WorldGeography*, with the same names as those indicated in the data item *MagnetRegionsPolygons* (compare the legend of the map with the names of the subcontainers in *MagnetRegionRuns* container, in the example provided in Fig. 7).

10.4.3 Preparing the LUM module for running a (set of) scenario(s)

Prior to running a scenario with the LUM, a number of data items may need to be adjusted by the user, such as those defining the number and name of scenarios to be run, the location of the directory with the INI files, and definition of modelling units such as gridcell resolution and time steps. These data items are specified in the *Parameters.dms* script file. Two options are available to open and edit this file (e.g. in a text editor such as Notepad++):

- Open the file directly from the GeoDMS GUI, by clicking on the *Parameters* container on the tree view, and then giving the shortcut command *Control+E* (or alternatively, right-clicking on the container and selecting *Edit Config Source*)
- Go to the folder *ModelConfiguration/LandUseModule/MagnetGridModel_LandUseModule* and open the file *Parameters.dms* (you may have to select the appropriate software).

The code lines related to the data items that may need adjustment are identified in the script with the marker *//@USER INPUT*, followed by an instruction on how to adjust the code. A comprehensive list of the code lines that can be adjusted by the user, and instructions on how to adjust them, is provided below. Note that only the parts of the code that are in bold should be adjusted. After making all the necessary adjustments to the data items described below, save the *Parameters.dms* file (e.g. using the shortcut command *Control+S* in Notepad++) and reopen the configuration file in the GeoDMS GUI (e.g. using the shortcut command *Alt+R* in the GUI), so that the changes in the configuration can take effect for the simulation of the scenario.

unit<UInt8> MagnetScenarios: NrOfRows = ***4***
{
*attribute<string> ScenarioName: [****‘Demo2018a’***
, ‘Demo2018b’
, ‘Project1/Demo2019a’
‘Project1/Demo2019b’*];*
}
Indicate here the number of scenarios to be run (on the unit property *NrOfRows*), and the name of the scenarios (on the attribute *ScenarioName*). Similarly to the SD and SCBA modules, also indicate the name of the project folder in the scenario name, in case the scenarios are part of a common project folder (e.g. *Project1/Demo2019a*). Make sure to keep the number indicated in *NrOfRows* in sync with the number of scenario names inserted in *ScenarioName*. Select here only a set of scenarios for which the parameters below can be specified in an identical way.

parameter<string> ScenarioSpecsFolder:
*Expr=“****‘D:/MagnetGrid_Validation/MagnetGridModel/ScenarioSpecs’****”*
Indicate the path for the *ScenarioSpecs* folder with the INI files for the scenarios mentioned in *ScenarioNames*.

*parameter <meter> GridcellResolution: Expr=“****10000.0****[meter]”*
Indicate the resolution of the gridcell (in metres) of the input spatial data that was exported from the SCBA module (i.e. region- and sector-specific land use and NPV maps).

*unit<float32> GridcellUnit: Expr = “Units/****lu100km2****”*
Indicate here the metric unit defining the gridcell area of the input datasets for the land-use spatial data. This unit should indicate the total area of the gridcell and should be derived from an existing base metric unit. Prior to adjusting this item, a new derived metric unit may have to be defined in the *Units* container. For example, in the demo version, the datasets with land-use data have gridcells representing an area of 100 km^2. For that purpose, the unit *lu100km2* has been defined in the *Units* container, as follows:
*unit<float32> lu100km2: Expr = “100.0 * luKm2”;*
lu100km2 is a derived metric unit that depends on the definition of the unit *luKm2*:
*unit<float32> luKm2: Expr = “100.0 * luHa*”;
Hence, *luKm2* is also a derived metric unit, which depends on the definition of the unit *luHa*:
*unit<float32> luHa: Expr = “10000.0 * Meter2”;*

luHa is also a derived metric unit, which depends on *Meter2*:
*unit<Float32> Meter2: Expr = “Meter * Meter”;*
Meter2 is a derived metric unit, which on the base metric unit *Meter*:
unit<Float32> Meter: Expr = “BaseUnit(‘m’, float32)”;
For defining a new derived metric unit, click on the *Units* container in the GUI tree view and use the shortcut command *Control+E* to open the *Units.dms* script file. Then, define a new data item by specifying its unit type (e.g. float32) and its metric relationship to an existing unit (base or derived). For example, if the gridcell area of the spatial input data for land use datasets is 25 km^2, a new unit could be defined as follows:
*unit<float32> lu25Km2: Expr = “ 25.0 * luKm2*”;

*unit<float32> ClaimsUnit: Expr =“Units/**claim100km2**”;*
Indicate here the unit defining the metric for the amount of land demand that has to be allocated. The *ClaimsUnit* should be defined in line with the unit specified in *GridcellUnit* so they have similar dimensions in relation to the base metric unit *Meter*. For example, in the demo version, the unit *claim100km2* is defined through a succession of derived metric units that is comparable to that of lu100km2, as follows:
*unit<Float32> claim100km2:   Expr = “100.0 * claimKm2”;*
*unit<Float32> claimKm2:   Expr = “100.0 * claimHa”;*
*unit<Float32> claimHa: Expr = “10000.0 * Meter2”;*
*unit<Float32> Meter2:   Expr = “Meter * Meter”;*
unit<Float32> Meter: Expr = “BaseUnit(‘m’, float32)”;
If the *GridcellUnit* is changed, then the *ClaimsUnit* also needs to be adjusted, and a new derived unit may have to be defined in the *Units* container. For example, if the gridcell area of the spatial input data for land-use datasets is 25 km^2, then a new claims unit could be defined as follows:
*unit<Float32> claim100km2:   Expr = “25.0 * claimKm2”;*

*unit<float32> MagnetClaimsUnit: Expr = “Units/**claimKm2**”;*
Indicate the unit defining the metric for the MAGNET land demand projections as given in the *MAGNET_data.csv* file. Typically, these projections are provided in km^2. Adjust only if the projections are given in a different metric (e.g. hectare – in this case, replace *claimKm2* by *claimHa*, which is already defined in the units container).

*parameter< MagnetClaimsUnit> ClaimsConversionFactor: Expr = “**100.0**[MagnetClaimsUnit]*
Specify the value for the parameter that converts the land demand projections from the original *MagnetClaimsUnit* metric unit (e.g. 1 km^2) to the *ClaimsUnit* metric unit (e.g. 100 km^2).

*parameter<Boolean> IsChangeClaimsAbsoluteValues: Expr= “**False**”;*
This parameter gives the option to select the method for calculating the changes in land demand between two consecutive time steps. Changes in land demand between time steps can be calculated either in absolute or relative terms. Calculating relative changes in land demand is useful when land use per sector in the starting year has not been harmonised between MAGNET projections, and the spatial datasets used as source data for land use in MagnetGrid (e.g. Earthstat, in the demo version). Calculating absolute changes in land demand is useful when it is important to ensure that the projections of agricultural land-use patterns obtained with MagnetGrid are fully aligned with the land demand projections from MAGNET. To select absolute changes in land demand as a method for calculating the land claims, inset *True,* otherwise *False*.

*unit<float32> NpvUnit: Expr = “Units/**EUR_ha**”;*
Insert the metric unit used in the valuation of NPV and all local utility components. In the demo version, utility and NPV are measured in EUR/hectare. This unit should be adjusted in case a different unit is used to calculate NPV and other utility components in the SCBA model.

*parameter<**luHa**> NpvLandAreaMagnet: Expr = “1.0[Units/**luHa**]”;*
This parameter is specified for the purpose of converting values of units among data items. Only the unit should be changed, according to the unit of the denominator in the *NpvUnit* data item. For example, EUR/hectare (i.e. *EUR_ha*) is the unit specified in NpvUnit in the demo version; therefore,

the parameter in NpvLandAreaMagnet is defined in hectares (i.e. *luHa*) unit values. Should the unit in NpvUnit be EUR/km^2 (e.g. *EUR_Km2*), then *NpvLandAreaMagnet* should be defined in km^2 (e.g. *luKm2*) unit values.

*parameter<Meter2> NpvLandAreaConversionFactor: Expr = "**10000.0**[Units/Meter2]";*
This parameter is also specified for the purpose of converting unit values among data items. In this case, the value of the parameter should be adjusted in case there is a change of unit values in *NpvUnit* and *NpvLandAreaMagnet*. In particular, it should indicate the relation between the unit values used in *NpvLandAreaMagnet* and m^2 (in the case of the demo version, hectares and m^2, therefore the value 10,000).

*parameter<YearRange> StartYear: [**2011**]*
*parameter<YearRange> SpoofStartYear: [**2010**]*
*parameter<YearRange> EndYear: [**2050**]*
*parameter<YearDiffRange> TimeStep: [**10.0**]*
The set of parameters specified above has the purpose of defining the time steps for the simulation of the scenarios. The parameter *StartYear* must indicate the first time step of the simulation, as referred in the *MAGNET_data.csv* file. The parameter *SpoofStartYear* must indicate a hypothetical first time step, had the first and second time steps been defined with the same regular interval as the remaining time steps. The parameter *EndYear* must indicate the last time step of the simulation. Finally, the parameter *TimeStep* should indicate the regular interval between time steps.

*parameter<Units/m2_Eur> betaFactor: Expr="**1.0**[Units/m2_Eur]";*
This parameter refers to the β parameter that adjusts the sensitivity of the logit model (see Eq. 1 and Eq. 3).

*parameter<Units/EUR_M2> NatureLandValue: Expr="**1.7**[Units/EUR_M2]";*
This parameter defines the economic value of nature areas. The current value is based on Koomen et al. (2015).

*parameter<Units/EUR_ha> NatureClearingCosts: Expr="**8000.0**[Units/EUR_ha]";*
This parameter defines the costs per unit of area of clearing land in nature areas. The current value is based on the review performed in Jacobs-Crisioni et al. (2017).

*parameter<Units/EUR_ha> NpvThreshold: Expr="**55000**[Units/EUR_ha]";*
Eventual artefacts generated throughout the modelling workflow may lead to unrealistically high values of NPV. This parameter defines a threshold for the highest NPV value possible, in order to ensure that numerical overflow does not occur during the simulation due to excessively high NPVs. The current value is based on Diogo et al. (2015), according to the NPV estimated for the best performing sector.

10.4.4 Running a (set of) scenario(s) with the LUM module

For running a scenario for a particular region, GeoDMS GUI can be used to navigate through the data items that are required to apply the allocation algorithm, to visualise (intermediate) results and export the resulting map projections of agricultural land use. The first step is to open the container that is specific to that scenario and region in the tree view. Within each region-specific container, there are three additional containers:

- *Simulation*, which includes all the data items required for the scenario simulation;
- *Endstate*, which gives the instruction to simulate the allocation of agricultural land use towards the last time step of the scenario;
- *ExportSimulationResults*, which gives the instruction to export the scenario results for all time steps and sectors.

Within the *Simulation* container, two containers are available:

- The *StartingState* container, which visualises the NPV and land-use maps in the starting year of the simulation. Fig. 8 shows an example with the land-use map for the wheat sector in India in the starting year of the simulation.
- The *TimeSteps* container, which calculates and visualises all the data items that are required for the simulation of each time step. Within this container, there is a subcontainer for each simulated time step (e.g. *P2020*, *P2030*, ..., until the last time step). Within each time-step container, there are two additional containers:
  – The *CaseData*, which includes all data items that are required as an input for the simulation of that time step, including the land use in the previous time step, the demand projections for that time step, the local utility components and the total local utility maps;
  – The *ResultingState*, which includes the data items related to the simulation results for that time step.

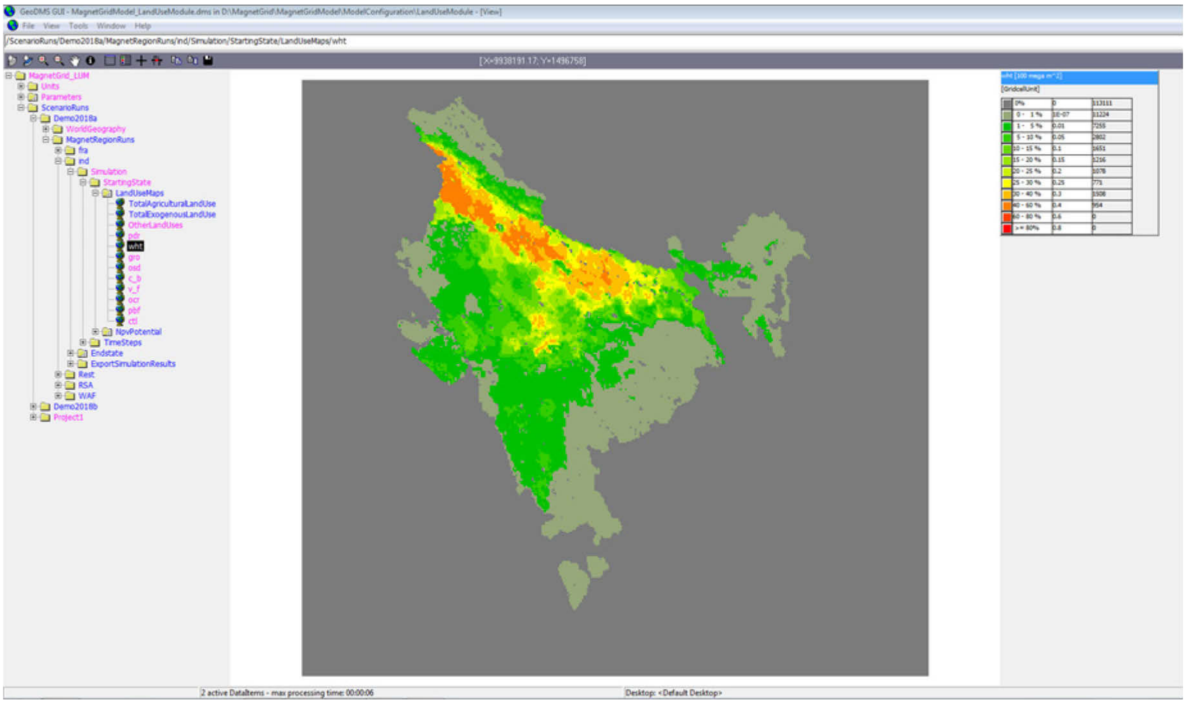

Figure 8 *GeoDMS GUI with the land-use map for the wheat sector in India in the starting year of the simulation for the Demo2018a scenario*

To visualise the data items that inform the scenario simulation of a time step for a particular region, navigate to the *Simulation/TimeSteps/CaseData* container on the tree view. Fig. 9, for example, shows the NPV map projections for wheat in India in 2020. To simulate a scenario time step in a region, navigate to the *Simulation/TimeSteps/ResultingState* container and click on one of the data items within that container. Fig. 10, for example, shows the map projection for the total agricultural land use of all agricultural sectors in India in 2020. To simulate all time steps in a region at once and visualise the end state of that scenario, navigate to the *Endstate* container and click on the data item *AllAgriculturalUses*. Fig. 11, for example, shows the map projection for the total agricultural land use of all sectors in India in 2050. Finally, to export the simulation results, open the container *ExportSimulationResults* and then click on the containers respective to each time step. The simulation results will be stored in the *LocalDataDir* that has been previously indicated as explained in Section 10.4.1 (e.g. *D:/LocalData*, see Fig. 6).

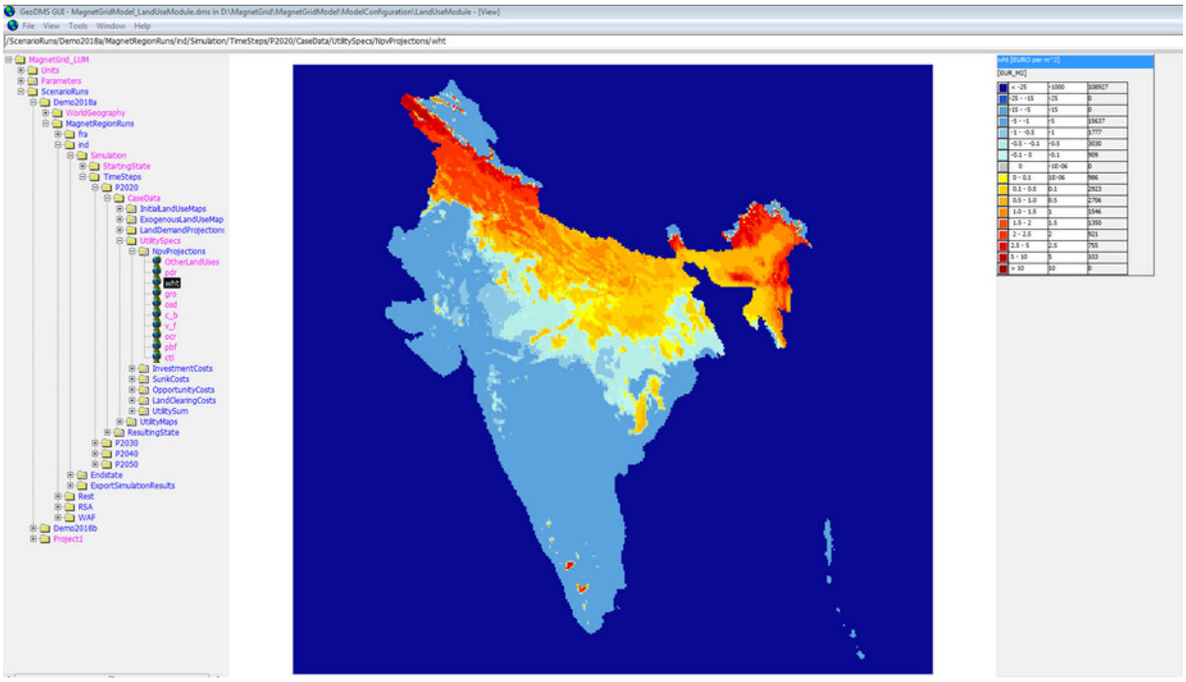

Figure 9 *GeoDMS GUI with the NPV map projection for the wheat sector in India in 2020 for the Demo2018a scenario*

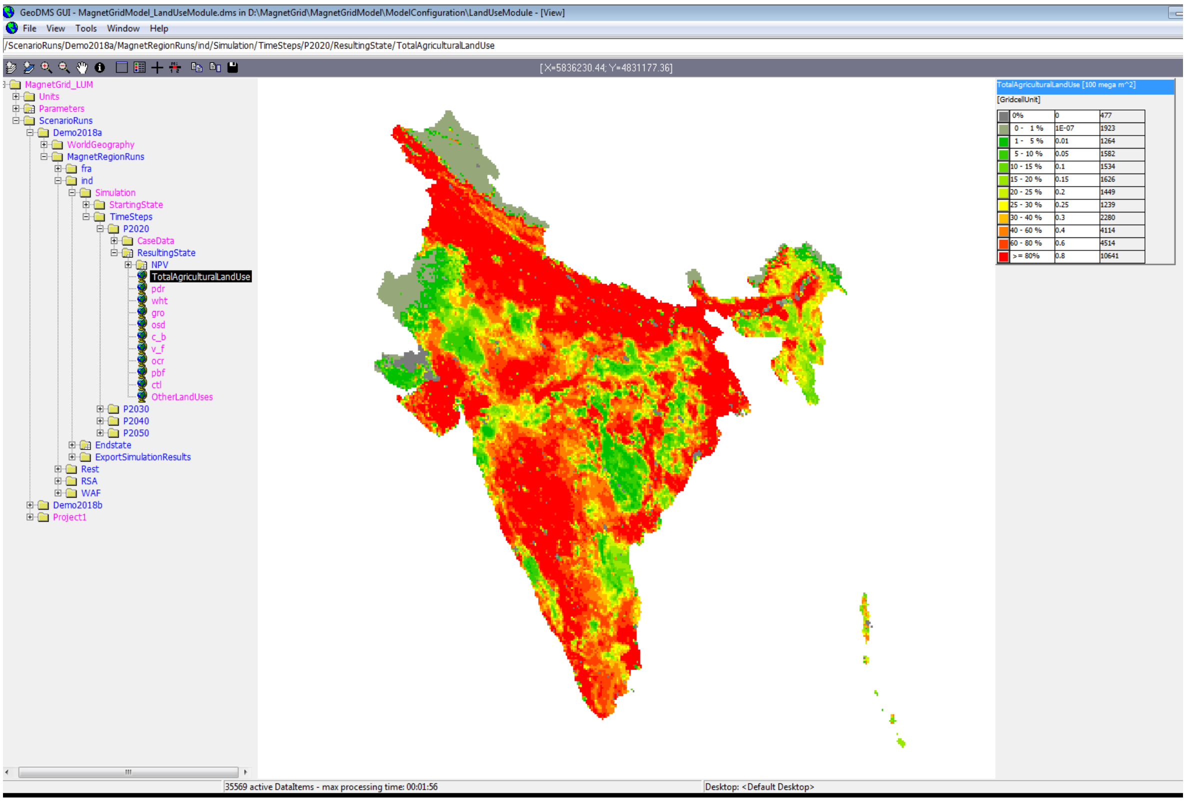

Figure 10 *GeoDMS GUI with the map projection for the total agricultural land use of all agricultural sectors in India in 2020, for the Demo2018a scenario*

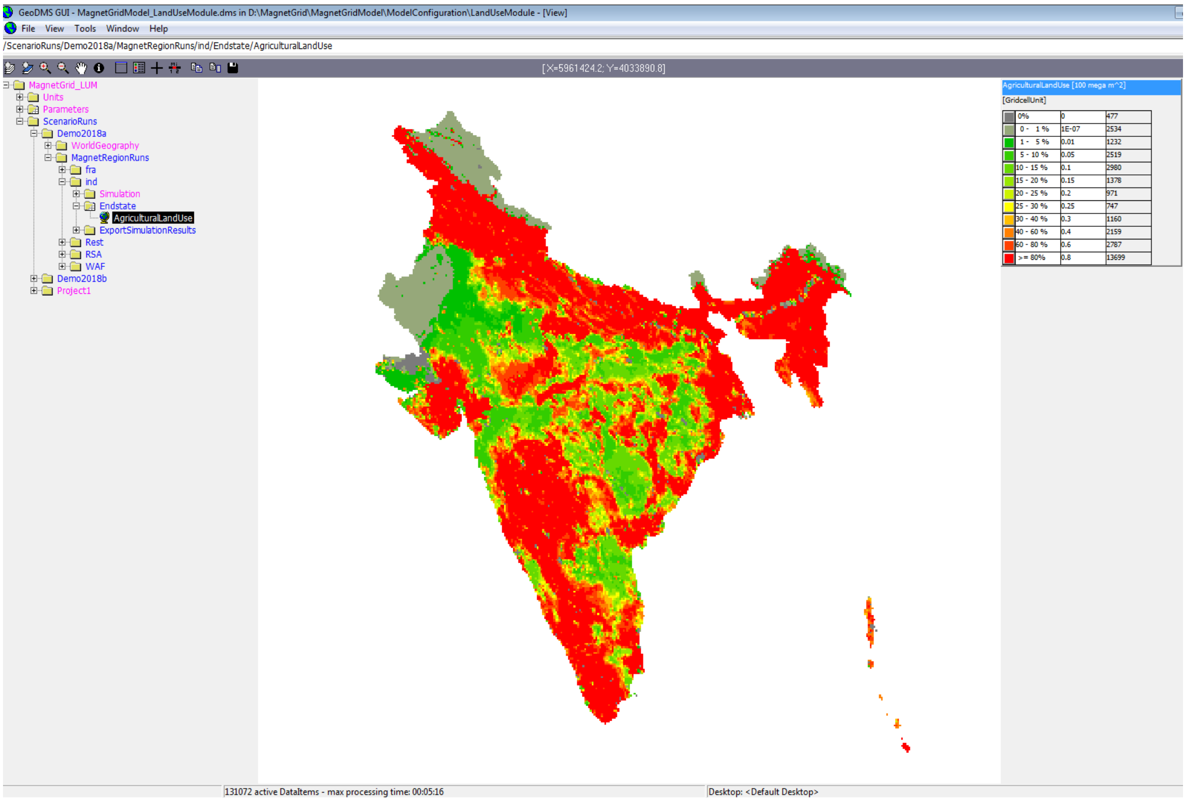

Figure 11 *GeoDMS GUI with the map projection for the total agricultural land use of all agricultural sectors in India in 2050, for the Demo2018a scenario*

It is also possible to run a series of scenarios and automatically export all simulation results, without having to interact with the GUI, by giving instructions through batch files directly to the GeoDMS modelling engine. An example of such batch files is provided in the folder *ModelConfiguration/LandUseModule/batchfiles*. Two .cmd files can be found:

- *RunMagnetGridScenario.cmd*, which gives general instructions about defining the path for the program files directory where the GeoDMS software is installed, the directory where LUM module script files can be found, the GeoDMS version in use and the function to be performed. An example for the configuration of this file is given below:

*set pf=“**Program Files**”*
*set MagnetGrid=**D:\MagnetGrid\MagnetGridModel\ModelConfiguration\LandUseModule***
*set geodmsversion=**GeoDMS7182***
call SelectMagnetScenarioAndRegions

- *SelectMagnetScenarioAndRegions.cmd*, which gives more specific instructions, such as selecting which scenarios, regions and time steps should be simulated, specifying the type of log file that should be stored, defining the path for the GeoDMS executable file, the .dms configuration file that should be read by GeoDMS, and finally indicating the data items that should be executed in order to run a complete scenario and export the respective simulation results (i.e. *EndState* and *ExportSimulationResults* containers). An example for the configuration of this file is given below:

set timestamp=%DATE:/=-%_%TIME::=-%
set timestamp=%timestamp: =%

for %%s in (Demo2018a, Demo2018b) do (
*for %%x in (**fra,ind,WAF,RSA**) do (*
*for %%t in (**StartingState,P2020,P2030,P2040,P2050**) do (*
c:\%pf%\ObjectVision\%geodmsversion%\GeoDmsRun.exe /Lbatchtrace_%%s_%%x_%timestamp%.log %MagnetGrid%\MagnetGridModel_LandUseModule.dms /ScenarioRuns/%%s/MagnetRegionRuns/%%x/Endstate/AgriculturalLandUse

```
/ScenarioRuns/%%s/MagnetRegionRuns/%%x/ExportSimulationResults/%%t/GeneratedFiles
                    )
          )
)
```

After specifying the batch files, run a set of scenarios by double-clicking on the batch file *RunMagnetGridScenario.cmd*. Similarly to running the module through the GUI, the simulation results obtained with the batch files are stored in the *LocalDataDir* folder. In addition, log files documenting the simulation calculations for each combination of scenario and region are stored in the *ModelConfiguration/LandUseModule/batchfiles* folder, with a time stamp on the file name.

11 Final considerations

In this report, we presented and described MagnetGrid, an innovative land-use modelling framework that simulates the global patterns of agricultural land-use change as a result of economics decisions on land. The multimodel framework combines modelling outputs from dedicated models that capture specific components of agricultural land systems, in order to provide integrated analyses that are both local-specific and contextualised in their wider regional and global contexts. The ability to address the causality between economic land-use decisions and their drivers with the resulting land-use change processes, while incorporating complex interactions with different types of factors operating across scales, implies that a coherent modelling approach for the simulation of agriculture land use has been established. Furthermore, the local utility valuation component of the framework can also be used within an integrated assessment framework as a tool for spatially explicit cost–benefit analysis of agricultural systems for different purposes, for example:

- analysing the impacts of climate change on the economic performance of agricultural systems, according to different climate and socio-economic scenarios;
- informing investment decisions in the agricultural sector, e.g. determining the economic feasibility of different climate-adaptation measures and the sensitivity to variation in key production factors;
- performing social cost–benefit analysis to explore the outcomes of changes in management practices and/or policy regimes, e.g. by monetising and internalising long-term externalities, such as GHG emissions, conservation of nature and infrastructure, water quality, and conservation of soils and landscape in the economic performance of agricultural systems.

A fully operational demo version of MagnetGrid modelling framework has been deployed. This demo version provides a highly flexible modelling environment based on templates, that can be relatively easily adjusted in order to run different scenario alternatives, update data sources and/or modify modelling units (e.g. spatial resolution, sector configuration, regional configuration, etc.). This flexibility allows for the implementation of the modelling framework in a wide range of applications, including global land-use change scenario projections and dedicated integrated analyses of agricultural land systems at the regional level. This report includes a user guide with a set of detailed instructions on how to install and operate the demo version of the model, and also on how to adjust it in order to implement it for the simulation of new scenarios and case studies.

Despite the auspicious prospects offered by the newly developed modelling framework, it should be noted that MagnetGrid is not a fully matured model yet. Hence, considerable efforts may still be required for achieving a fully competent modelling framework. A tentative, incomplete list of issues to be addressed and recommended pathways for further development and improvement of the modelling framework is provided below.

- **Model validation:** The presented land-use modelling framework relies on a one-dimensional utility function based solely on the principles of profit maximisation. This type of approach has demonstrated that it is capable of reproducing agricultural land-use change patterns in study areas where the agricultural sector is essentially composed of advanced commercial production systems in a free-market setting and land rights are well defined (see for example Diogo et al., 2015; Koomen et al., 2015). It is, however, unclear whether such an approach is the most appropriate method to describe observed land-use change processes in developing regions where subsistence agriculture is prevalent, land rights are often poorly defined and/or power and information asymmetries might exist among different types of actors. A validation exercise is currently ongoing to assess the ability of MagnetGrid to reproduce observed land-use patterns in different world regions. The results of this exercise will be important for grasping the potential merits and limitations of the proposed modelling framework, as well as identifying further refinement of the utility function to better capture heterogeneous sets of producers.

- **Adjustment of the spatial model and allocation algorithm so that projected total regional production per sector is allocated by the model, instead of projected total land use area**: The spatial land-use model and land-use allocation algorithm described in Sections 4 and 5, respectively, take MAGNET projections on regional land demand per sector as a leading factor for the simulation and allocation of land use. These projections are, however, based on average regional productivity levels, while local productivity may vary considerably within a region. Hence, the total production levels that are achieved on the land units allocated by MagnetGrid may actually differ on aggregate from those projected by MAGNET. This potential inconsistency will be verified in the forthcoming model validation exercise. Depending on these results, it may be worth considering an adjustment to the spatial model and allocation algorithms, in order to ensure the consistency between the two models in terms of regional production levels.

- **Practical implementation of the modelling framework for running a scenario:** Although the demo version of MagnetGrid is currently fully operational, the actual application of the modelling framework for running a well-defined scenario has not been entirely demonstrated yet. In particular, the ability to coherently combine scenario projections from MAGNET and from a gridded crop growth model (e.g. LPJmL), and subsequently integrate them within MagnetGrid, has not been fully tested. Coupling models and operationalising their linkages can be a challenging endeavour though (see for example Kling et al., 2016), as follows:
  - Scenario storylines need to be coherently elaborated and operationalised in the different models.
  - The underlying data describing the biophysical and economic systems should be internally consistent; e.g. changes in biophysical suitability due to climate change as simulated by crop growth models should be accounted for in MAGNET simulations; MAGNET variables on sector land-use and land availability in the starting year should be derived from the same spatial data that is used in MagnetGrid.
  - Consistency of the component models in terms of scale, regional coverage, and inputs and outputs at system boundaries needs to be ensured. For example, modelling units such as baseline crops/commodities that are simulated in crop growth models, and their aggregation to agricultural sectors in MAGNET and MagnetGrid, need to be fully aligned across models.

  It would therefore be crucial for the enhancement of the modelling framework to apply it for the simulation of a reference scenario, as a way of testing its implementation in practice, and also for establishing standardised procedures and best practices for coupling the different models in forthcoming studies.

- **Improvement of the characterisation of grazing livestock sectors in the model:** In the current demo version, the characterisation of grazing livestock sectors is done in a relatively simplistic way, for example:
  - Grassland land cover from EarthStat is currently used to represent livestock land use in the starting year of the simulation. Since it is not possible to distinguish the actual land use by different types of livestock based on a land cover dataset, only one livestock sector can currently be simulated in MagnetGrid. A promising alternative is to use livestock distribution maps from GLW database for the year 2010 (Gilbert et al., 2018; https://dataverse.harvard.edu/dataverse/glw) as a data source to derive land-use maps for representing different types of livestock sector[2]. The cross-disciplinary framework proposed in Phelps and Kaplan (2017) could potentially be used as a basis to inform the method for deriving such maps.
  - The specification of local utility for livestock sectors disregards many important aspects related to management strategies in animal production. For example, grass suitability is currently used in the model as a proxy for representing potential local productivity. However, in reality livestock systems are characterised by the use of a combination of different types of feed (including, for example, grass, silage maize and feed concentrates), that can vary widely across regions and considerable influence not only productivity but also production costs. Efforts should be made in

[2] A complete characterisation of land use for the year 2010 could be achieved by using crop land use maps from MapSPAM for the year 2010 (You et al., 2014; http://mapspam.info/) as a data source for the representation of non-livestock sectors. Should this be the case, the year 2010 could then be considered as the starting year of the simulation for all sectors.

explicitly characterising animal production systems in different world regions in order to improve their respective specifications of local utility.

- **Inclusion of forestry and bioenergy crop sectors as endogenous land-use types:** MAGNET provides scenario projections on the forestry and bioenergy sectors. Methods should be developed for the spatially explicit valuation of local utility for these sectors, so that forestry and bioenergy can be explicitly simulated in MagnetGrid as additional sectors competing with food production for land.

- **Incorporation of scenario projections of urban land use:** In the current demo version, urban land use is implicitly considered to be static (see Section 10.2.5). However, urban areas are expected to expand considerably in the coming decades, due to a combination of global population growth and increased urbanisation (UN, 2019). The option to explicitly incorporate scenario projections of urban development from global urban land-use models such as PBL's 2UP model (Van Huijstee et al., 2018) should therefore be explored.

- **Incorporation of policy mechanisms and investments with a territorial dimension in the modelling framework and scenario definitions**: This could include the enforcement of nature protection zoning policies, development of transport infrastructure, water management and irrigation infrastructure.

- **Improvement in the calibration of the global model parameters towards region- and sector-specific parameters:** In the current demo version, a few parameters are globally specified, i.e. the same values are attributed to different world regions and sectors. Effort should be put into improving the calibration of such parameters to make them region- and/or sector-specific, for example:
  - NPV parameters such as discount rate, lifetime and NPV threshold (i.e. the maximum NPV that is considered to be realistically achieved in the region);
  - Land clearing costs and nature valuation, for which different types of passive land-use types should be distinguished (e.g. rainforests, temperate forests, savannah, shrubland).

- Improvement in the specification of local utility when applying MagnetGrid as a spatial cost–benefit analysis tool for dedicated case studies: The current specification of local utility has a number of limitations that are deemed acceptable when applying the framework for simulating global land-use patterns, but that should be addressed when assessing the NPV of agricultural sectors in more detailed case studies at the regional level, for example:
  - Fixed and variable production costs should be distinguished (Section 6.1.2).
  - Transportation and other logistics costs should be estimated and included in the NPV valuation, for example by taking into account global maps of accessibility to cities (Weiss et al., 2018, https://map.ox.ac.uk/research-project/accessibility_to_cities/) as a proxy for distance to markets.
  - Sector suitability should take into account the actual crops that are grown in the different agroecological zones of a region.

- **Inclusion of spatial variability of economic agents:** Producer and consumer characteristics may affect land-use decisions, for example through the competition of farm and non-farm activities for labour and capital, or the need to produce food for household consumption. Explicitly accounting for agent heterogeneity and interactions across space would allow for more refined food security assessments, providing spatial as well as household variability in impacts. Such an extension could build upon recent work using spatial information from LSMS household surveys available for many lower-income regions, with crop suitability maps and models (see for example Wichern et al., 2017 and Waha et al., 2018).

- **Exploration of the inclusion of feedback mechanisms across models:** The proposed multimodel framework addresses dynamics and interactions among drivers at different scales in an efficient and flexible manner. However, the current modelling workflow implies a unidirectional coupling of the models that does not allow the incorporation of important feedback mechanisms between biophysical and economic systems. Fig. 12 illustrates potential feedback loops across models (as red arrows) that could be further explored.

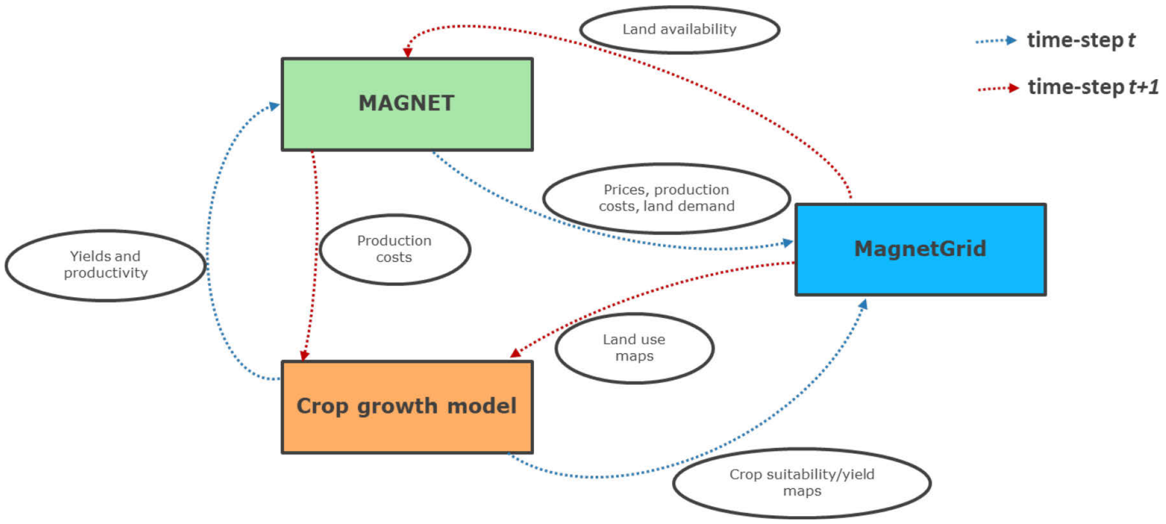

Figure 12 *Potential feedback linkages across models*

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The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 5,000 employees and 12,000 students, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.