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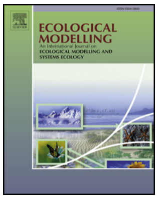

Multi-objective land use allocation modelling for prioritizing climate-smart agricultural interventions

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ABSTRACT

Climate-smart interventions in agriculture have varying costs and environmental and economic impacts. Their implementation requires appropriate investment decisions by policy makers that are relevant for current as well as future scenarios of agro-ecology, climate and economic development. Decision support tools are therefore needed to assist different stakeholders to prioritize and hence implement appropriate strategic interventions. These interventions transform agriculture ecosystems to climate-resilient, adaptive and efficient. This paper outlines the mathematical modelling framework of one such, the Climate Smart Agricultural Prioritization (CSAP) toolkit. This toolkit employs a dynamic, spatially-explicit multi-objective optimization model to explore a range of agricultural growth pathways coupled with climate-adaptation strategies to meet agricultural development and environmental goals. The toolkit consists of three major components: (i) land evaluation including assessment of resource availability, land suitability, yield and input-output estimation for all promising crop production practices and technologies for key agro-ecological units; (ii) formulation of scenarios based on policy views and development plans; and (iii) land-use optimization in the form of linear programming models. Climate change and socio-economic drivers condition the land evaluation, technological input-output relations, and specification of optimization objectives that define modelled scenarios. By integrating detailed bottom-up biophysical, climate impact and agricultural-emissions models, CSAP is capable of supporting multi-objective analysis of agricultural production goals in relation to food self-sufficiency, incomes, employment and mitigation targets, thus supporting a wide range of analyses ranging from food security assessment to environmental impact assessment to preparation of climate smart development plans.

1. Introduction

The Climate Smart Agriculture (CSA) is an integrative approach to address the interlinked challenges of food security, climate change impact, and ecological sustainability (Lipper and Zilberman et al., 2018; Steenwerth et al., 2014). To achieve these, three objectives are defined: (i) sustainably increasing agricultural productivity to support equitable increase in farm incomes, food security and development; (ii) adapting and building resilience of agricultural and food security systems to climate change; (iii) and reducing greenhouse gas emissions from agriculture (FAO, 2013). A range of technological, institutional and policy options has been proposed to help agriculture become climate-smart, including weather insurance, spatial weather forecasts, agricultural diversification, stress-tolerant crop varieties, community management of soil and water resources, and policies related to water and carbon management (Thornton et al., 2017; Shirsath et al., 2017; Khatri-Chhetri et al., 2017; Long et al., 2016; Lipper et al., 2014; Vermeulen et al., 2012). These interventions have varying costs and economic impacts. Moreover, the effectiveness of these interventions depends on agro-ecological condition of a region and their adoption is highly influenced by the socio-economic characteristics of the agrarian society of that region (Khatri-Chhetri et al., 2017; Sapkota et al., 2017). Therefore, the implementation of CSA requires appropriate investment decisions in both on-farm capital and wider agricultural outreach

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programmes. Furthermore, climate-smart investment can have a wide range of scales ranging from the single field up to the national level. It is unlikely that investment in any single intervention will provide optimal benefits, but rather an integrated portfolio of interventions is required to best support adaptation to climate change in agriculture across a range of scales. This spatial complexity is compounded by the long timeframes associated with climate change, requiring further consideration of when as well as where to prioritize investment in any set of intervention options. If climate-smart technologies provide net benefits to farmers irrespective of climate change – so termed no-regrets options (Thornton and Lipper, 2014; Willows and Connell, 2003) – then the investment is preferred as soon as possible. However, given the costs of investment in the short-term under constrained budgets, and with the benefits of adaptation, increasing with the progressive impacts of climate change, it may be preferable to delay investment until full benefits can be realised. Decision support tools are therefore needed that can assist different stakeholders to prioritize appropriate and timely strategic interventions to transform agricultural practice to become climate-resilient, efficient and adaptive (Tanure et al., 2013). Given the competing social, economic and environmental dimensions of adaptation decisions, Multi-Criteria Analysis (MCA) is becoming increasingly popular in supporting the development of adaptation strategies. MCA differs from traditional risk management tools. It can retain competing objectives separately rather than aggregating them into a single, weighted decision metric (Willows and Connell, 2003). MCA (Prabhakar, 2014; Feltmate and Thistlethwaite, 2012; Lobell et al., 2008) and tools based on MCA such as Adaptation Decision Matrix (ADM) (Mizina et al., 1999) have been used widely in prioritizing technology options in agriculture. Several other tools such as fuzzy-analytical hierarchical process (Sanneh et al., 2014) and crop simulation model-based adaptation decision tools (Webber et al., 2014) have also been used. Several other tools and methodologies including participatory methods (Arshad et al., 2017; Khatri-Chhetri et al., 2017; Mwongera et al., 2017; Taneja et al., 2014) have been reported for adaptation prioritization (e.g., Willows and Connell, 2003; Lobell et al., 2008; Cross et al., 2012; Sanneh et al., 2014; Webber et al., 2014; Ilori and Prabhakar, 2015; Brandt et al., 2017). However, there is a lack of dynamic and spatially-explicit optimization tool to explore a range of agricultural growth pathways under different climate change scenarios.

This study presented here builds over work done by Shirsath et al. (2017), where prioritization of the climate-smart agricultural land use options at a regional scale were showcased using the databases generated through a spreadsheet-based methodology. In this methodology, however, the pillars of climate smart agriculture were treated separately and finally integrated through climate smartness index. The climate smart agriculture has a wide range of objectives including – food security, increase in farmers' net income, improvement in resource use efficiency, climate resilience, and GHG mitigation. The single objective models cannot take into account the trade-offs or synergies between economic efficiency and environmental efficiency which was not addressed in the earlier work using detailed bottom-up biophysical and socio-economic databases as described by Shirsath et al. (2017). Therefore, a multi-objective modelling framework with detail consideration of spatial heterogeneity in terms of bio-physical characteristics and resource endowments is necessary to make CSA adoption decisions for a range of stakeholders. Given this motivation, we have taken into consideration multiple objectives for optimization purpose. In addition, the trade-offs among the various competitive (optimal) solutions (corresponding to different objective function) has been considered to estimate the decision space which will minimize the trade-offs among the competitive objectives so that climate smart technologies can be prioritized in more sustainable manner. Hence, this paper outlines a multi-objective prioritization toolkit based on a spatially explicit bottom-up biophysical framework, and demonstrates a case study for prioritization of CSA technologies in Bihar state, India. The toolkit supports analysis of trade-offs between objectives and identification of efficient solutions. Results shows that the toolkit is capable in optimizing different adaptation options based on bio-physical conditions of a particular location.

2. Materials and methods

2.1. Model description

In its current formulation the Climate Smart Agricultural Prioritization (CSAP) toolkit is flexible in its capability to model agricultural production at a wide range of spatial and temporal scales. A typical analysis with the CSAP toolkit starts with the identification of land units, which define the spatial resolution of the study, and then proceeds with preparation of biophysical and socio-economic datasets for the multi-objective analysis. Although database development and multi-objective analysis can be developed separately, we recognise that they are highly interdependent, in view of the nature of the explicit assumptions made during development of both the database and the toolkit. Application of the CSAP toolkit therefore encompasses all stages of data processing, assumption setting (e.g. land-unit, season and crop suitability) and mathematical model formulation. A simple flow-chart outlining this process is shown in Fig. 1.

2.1.1. Spatial land units

The effectiveness of technological interventions is strongly determined by local bio-physical conditions, climate change impacts,

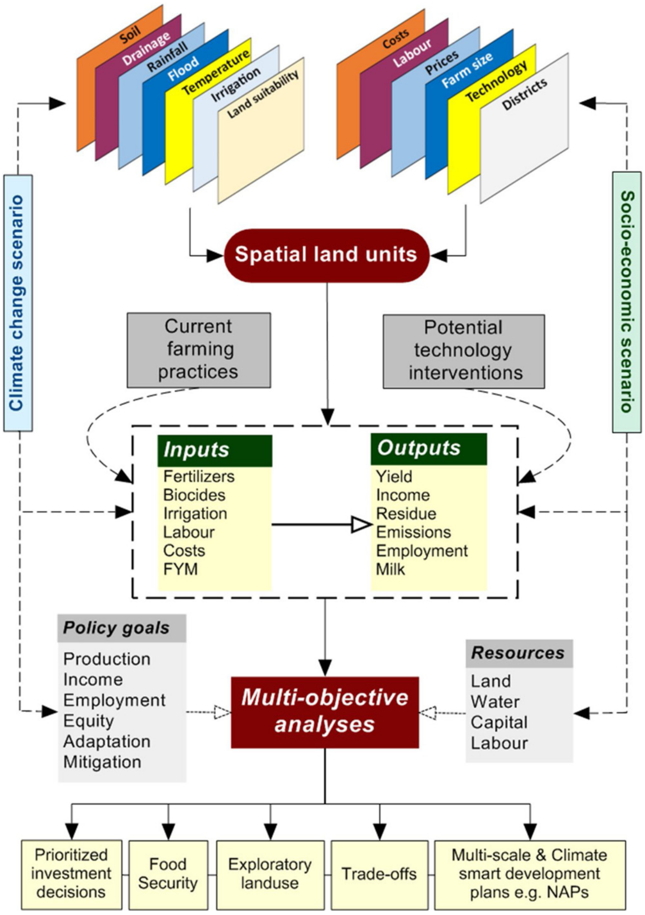

Fig. 1. Schematic diagram of the CSAP toolkit illustrating key component and their relationship. White arrows with solid outline indicates use of transfer functions for output calculations. White arrows with dashed outline indicates modular choice options for selection of the objectives and the resources constraints.