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Phosphorus Use and Management Strategies: Exploring Scenarios of Smallholder's Soil Fertility, Food Production and Livelihood with a Multi-Agent System Model

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Abstract: Phosphorus (P) is a key nutrient for food production. However, excess P use, e.g. in form of inorganic fertilizer application, can lead to environmental pollution, biodiversity losses and low profitability. Continuous cultivation with underuse of P fertilizer results in low food productivity and soil degradation due to soil nutrient mining or soil erosion. The concern is most serious for smallholder farmers in developing countries whose food production and livelihood is tied directly to their access to and efficient use of P as key nutrient for plant growth. This paper introduces a multi-agent system modeling framework for assessing long-term impacts of integrated P nutrient management options on soil fertility, food productivity and profitability of smallholder agro-ecosystems in different geographic regions. We consider Vietnam's smallholder systems in the Red River Delta (P overuse, market-oriented) and in the Northwest Mountain Region (P underuse, subsistence) as case examples for the two contrasting P use regimes. The model is planned to be used for informing trade-offs between long-term benefits and costs driven by different P management strategies and policies in a multi-stakeholder discourse.

***Keywords**:* Phosphorus, soil fertility, food production, smallholder, agent-based model, multi-agent system, transdisciplinary process, Vietnam

1 INTRODUCTION

Sustainable phosphorus (P) management has been recognized as an emerging global issue [Syers et al. 2011]. Being a key, yet non-substitutable, nutrient for biological production, P availability has an enormous significance for global food security. Extreme statuses of plant-available P in the soil have substantial human and environmental costs. Deficits of soil plant-available P certainly limit crop yields [Syers et al. 2011], but its excessive status acts as a driver of eutrophication in water systems [Elser and Bennett 2011], biodiversity decline [Wassen et al., 2005]. Studies suggest that human activities have more than tripled global P flows to the biosphere compared to pre-industrial levels, causing soil degradation and water pollution, environmental problems which in turn constrain food production [Smil 2000, Elser and Bennett 2011]. The concern is most serious for smallholder farmers in developing countries, representing more than 75% world's rural population, whose livelihoods and challenges of malnourishment and poverty are tied to environmental quality and soil productivity [World Bank 2010]. Globally, unsustainable P management and subsequent challenges on smallholders fall largely into two P use regimes: Many smallholders are involved in fertilizer–dependent intensified production to meet new market demand for food, promoting P fertilizer *overuse* and farmer vulnerability to increases in fertilizer prices. Another large group of poor subsistence smallholders cannot gain access to fertilizers, where P fertilizer is *underused*, leading to soil degradation exacerbating poverty. Therefore, viable options for economically and environmentally efficient P resource use and recycling in such smallholder agro-ecosystems need special attention.

Although a great deal of knowledge on ways to efficiently use and recycle P in agriculture exists, too few studies seek to understand how agricultural policy, financial services, farming technologies, local capabilities interactively affect smallholders' decision about nutrient use and management. Additionally, how such decisions affect soil fertility, food productivity and profitability of the whole farm has not been sufficiently investigated yet. Human decision-making at multiple levels, interactions between agro-ecosystem components, and their dynamics over time and space are keys to understand (potential transitions towards) sustainable P use. Given that human and environmental dimensions of agro-ecosystems are inextricably intertwined, research on such sustainable transitions needs to examine relevant aspects of the underlying coupled human-environment system (HES) [Scholz 2011]. Although multi-agent system (MAS) simulation has been recently recognized as a promising approach for explaining complex human-environment interactions in smallholder agro-ecosystems [Matthews 2006], so far no HES-MAS model with a P-use focus that fits the need stated above has been developed. This paper conceptualizes and describes a **M**ulti-**a**gent system model for exploring efficient smallholders' **P u**se and management strategies (MAPU).

2 BASIC PRINCIPLES AND PRELIMINARY TOOLS FOR MODEL DEVELOPMENT

Because the human and environmental dimensions of the farming system are inextricably intertwined, MAPU represents a smallholder community as the coupled human-environment system (HES). We use the HES-framework, recently proposed by Scholz [2011], as the conceptual guide for analyzing the dimensions of sustainable P use and management. We characterize the farm environment with a focus on P nutrient dynamics across farm's units (soil, crop and livestock) and interrelated crop yields, and the responses of these dynamics to change in P fertilizer use and/or waste recycling. It is important to understand how farmers decide which crop and fertilizer management strategies to apply in response to different individual and contextual constraints/opportunities. The factors affecting farmer decision on fertilizer use and waste recycling are diverse: household status, farm environment, past experience, neighborhood conditions, policy constraints/opportunities, fertilizer and food market, financial services and land tenure [Roy et al. 2006]. The smallholder agent is viewed as part of local and regional communities, where flexibility, ability to learn, and network-building promote success. A major focus of the investigation will be on identifying relevant human actors and environmental factors at regional and local levels, and how they interact. Finally, it is important to know the degree to which farmers, development practitioners, policy-makers are aware of the role of P use for securing farm productivity and livelihood.

The MAPU model is a further development of the LUDAS model [Le et al. 2008, 2010, 2012]. LUDAS is a multi-agent system model for spatial-temporal simulation of a coupled human–environment system. The model falls into the class of *all agents*, where the human population as well as the landscape environment are self-organized interactive agents (i.e., households and land units). Advantages of the LUDAS model compared to other MAS models lie in its capability to capture secondary feedback loops and different types of human adaptations [Le et al. 2012, Villamor et al. 2011]. As the LUDAS model was originally developed in the Vietnamese rural context, the social-ecological relevance and the feasibility to develop MAPU model based on LUDAS are high.

While the HES-framework provides important postulates to generally analyze the smallholder farming system, the Sustainable Livelihood Framework (SLF) [Bebbington 1999, Ashley and Carney 1999] is used for specializing livelihood-relevant variables of the household agent. The livelihood framework includes five core asset categories: *human*, *social*, *financial*, *natural* and *physical* assets. This spectrum of livelihood assets is the basis of farmer's capacity to generate new activities in response to needs and opportunities. The concept forms a theoretical basis for deriving indicators to assess the performance of natural resource management and helps to avoid bias in the selection of indicators from one particular discipline [Le et al. 2012]. The focus will be P uses within farmers' livelihood strategies - ways of combining and using assets – which farmers perform to reach livelihood outcomes.

Since the nutrient stock-and-flow network in smallholder farms was well-represented by the NUTMON model [den Bosch et al. 1998a, 1998b] and Shepherd's model [Shepherd and Soule 1998], we utilize the configurations of these models to represent the farm environment with a focus on P nutrient flows. However, in contrast to the static and accounting framework of NUTMON, MAPU represents the farm production units (e.g. soil, crop, livestock) as autonomous and interactive agents which are encapsulated by biophysical attributes (e.g. nutrient contents) and sub-models (e.g. models for predicting plant-available P, P-loss by soil erosion, and yield response). Interactions between these biophysical agents will be formed by the flows of nutrients that are controlled by household agent's activities.

A critical limitation of many real-world MAS models is their low robustness in coping with changes in the contextual and boundary conditions. To accurately mimic the complex social-ecological system, many MAS models are too much site-specific in terms of their assumptions and structures. This makes the model performance site-dependent and incapable to respond to a wide range of driver configurations. To increase the robustness of the MAPU model, our strategy is to develop *one MAS model* that is applicable to the two contrasting farming/P-use regimes (subsistence/P-underuse and market-oriented/P-overuse), and responsive to a wide range of drivers for smallholder system dynamics.

3 STUDY AREAS AND DATA

The geographic scope for this study is considered at two levels: (1) the geographic context and (2) the working areas. The geographic context refers to a broad agro-ecological region that shapes the identification and analysis of representative cases, and the generalization of the study findings. Based on a review of the existing world farming systems classification [Dixon et al. 2001], the global pattern of agronomic P balance [MacDonald et al., 2011], together with our current collaboration network, we focus on the 'lowland rice-based farming system in Eastern Asian tropical monsoon climate', and 'Highland extensive mixed farming system in Eastern Asian tropical monsoon climate' [Dixon et al. 2001] intersected with 'over P use' and 'under P use' regions [MacDonald et al. 2011], within one country (Vietnam). Next, through considering the national patterns of climate, soil, demography and land uses, we identify Hiep Hoa (Red River Delta, market-oriented system, P-overuse) and Yen Chau (Northwest Mountain Region, subsistence system, P-underuse) as our working case areas. Characteristics of the geographic contexts and working case areas can be found in a novice guide of the Global TraPs Project [2012]. Data for model parameterization and validation are based on two-level field studies: (1) extensive farm survey across the study areas for characterizing social-ecological patterns and system initialization, (2) in-depth survey of a limited number of representative farms (about 6–8 farms/area) for quantifying P flows and agent's functions (database not shown).

4 MODEL DESCRIPTION

To facilitate readability through stipulating a structure for description with a logical ordering, in this paper we briefly describe the MAPU model using ODD (Overview, Design concepts, and Details), which is a standard protocol for describing individual- and agent-based models [Grimm et al., 2006].

4.1 Overview

Purpose: The MAPU model is designed to assess long-term impacts of integrated P nutrient management options on soil fertility, food productivity and profitability of smallholder agro-ecosystems in typical farming regions in Northern Vietnam or other similar regions. Thereby we scientifically support a multi-stakeholder discourse for realizing orientations of sustainable P use and management. The model has its meaning only in the assessments of relative ex-ante impacts based on comparative analyses of multiple driver-induced outcomes, rather than the predictions of the absolute magnitude of the impacts.
External drivers: External drivers considered include (1) agricultural and land-use policy, (2) market factors, (3) rural financial services/institution, (4) innovation in farming technologies, and (5) local capabilities. Consistent future scenarios of these factors will be generated using Formative Scenarios Analysis [Scholz and Tietje 2002].

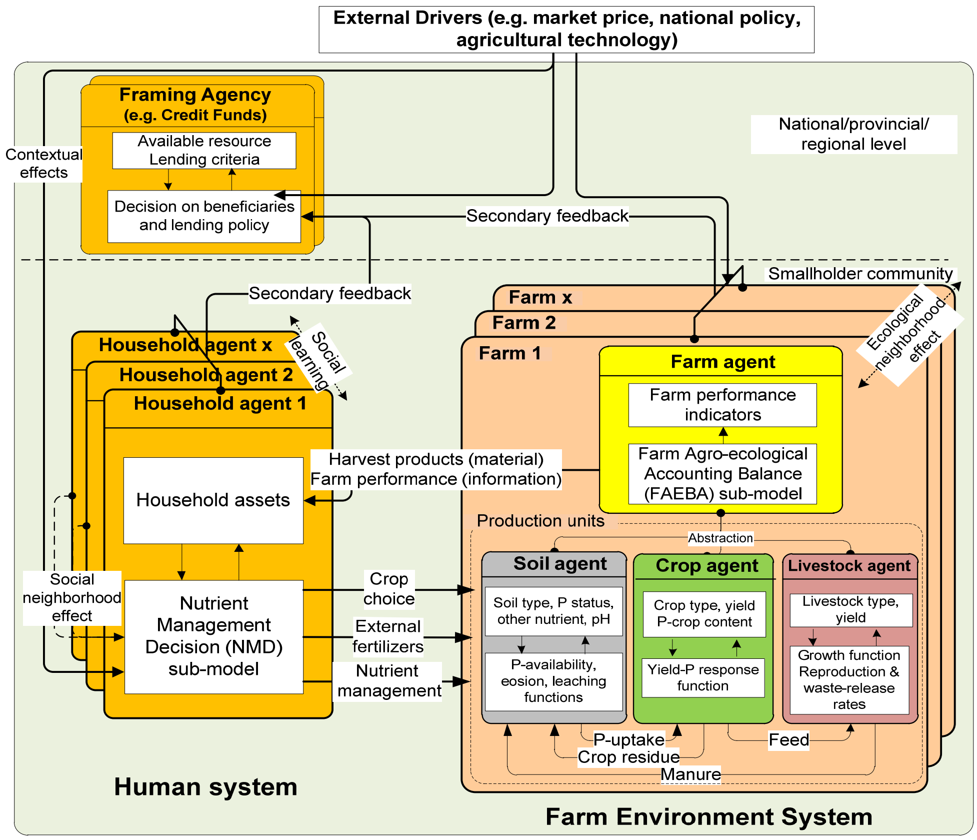

Figure 1. The agent-based block diagram of MAPU

Entities, state variables, and scales: The hierarchy of human and environmental agents and their variables in the MAPU model are visualized in Figure 1. The smallest unit for representing the farm landscape environment is the *farm agent*. It is comprised of three production units: a *soil agent*, a *crop agent*, and a *livestock agent*. A soil agent represents the top layer of soil on the farm parcel with (1) topographic attributes and soil properties and (2) functions/sub-models accounting for soil P dynamics in response to natural and human factors. A crop agent represents crops grown on a farm parcel. Its variables include parcel location and area, crop type, cultivation method, crop yield, and P-crop content. A livestock agent describes a livestock production unit that contributes to nutrient flows across the farm. Variables of the livestock agent include livestock population, livestock type, and livestock production yield and waste. The farm agent represents the farm as the whole and has its own variables that include agronomic, ecological and economic performance.

The human system is represented by *household agents* and *framing agents* and interactions between them. The *household agent* is the smallest unit for measuring human dimensions of the system, using a year time step. A household agent has its own state and decision-making mechanisms for managing farm resources (soil, crop and livestock). The household profile is represented by variables for social, human, financial, natural and social capitals of the household livelihood. A *livelihood type/group* is a collection of households having similar livelihood structure and behavior patterns. Because the behavioural strategy of a household agent can change over time, parameters specifying household behaviour are also treated as state variables and are stored in the memory of household agents. The framing agent represents the human dimension of the system at a regional or national level, which has long-term responsibility for sustainable agriculture and food security. One example likely to be included is a regional credit agency, which has great influence on farmers' decision-making process regarding farm nutrient management [Roy et al., 2006].

Process overview and scheduling: The initial grid-based landscape is given by GIS raster files of corresponding variables. The initial population of household agents is generated from a set of sampled households. Parameters of considered policy and P management options are defined by users. In a MAPU run, the coupled human-environment system is seasonally successive. In most cases, all household, farm, soil, crop, and livestock agents are called upon to perform tasks in parallel. The model is coded using NetLogo version 4.1x [Wilenski, 1999].

4.2 Key design concepts

***Agent's objectives*:** Goal-seeking in a household's decisions is explicitly modeled. Households calculate utilities (expressed in a probability term) for all crop types and P-use/recycling alternatives and select the alternative with the highest utility with a certain likelihood. However, by applying an ordered choice algorithm [Le et al. 2008], concrete household's decisions in MAPU are bounded-rational rather than purely rational. This holds the risk that some household agents select an option that may not be the best, but the chance for choosing the best alternative is high.

Interaction: In MAPU, agents interact indirectly or directly. Indirect interactions among household agents involve the fact that the change in structure, practices and performance in one farm will create change in the sensing/learning sphere of the other household agents, eventually influencing their decisions. Direct (material-based) interactions between soil, crop, livestock and household agents include two types: interactions controlled by natural process (e.g. soil P nutrient update by crops), and interactions controlled by households (e.g. use of crop product to feeding animal, reuse of manure as organic fertilizers). Interactions between agents lead to a *human-induced feedback loop system* in smallholder farming system, in which the feedback structure is dynamic, depending on agent's decisions.

Feedback loops, learning and adaptation: Adaptive decision making of human agents involves primary and secondary feedback loop learning. The primary feedback loop involves direct information and material flows between household agents and their farm environment. Household agents perceive the biophysical state of their farm and the past performance of their production activities. They use that knowledge to anticipate benefits of alternatives that are compared for arriving at their decisions. The soil environment responds directly to crop and fertilizer use activities in terms of plant-available P in soil, crop and livestock yields. This primary feedback learning does not alter the goal-oriented decision rules of agents.

The secondary feedback loop learning is defined by household-driven cumulative changes in household livelihood and farm environment on larger scales and in the longer term (possibly unintended), leading to the reframing of the agent's behavioral program. Household agents can change their behavior strategy by imitating the strategy of the most similar household group. Because secondary feedback loops involve changes in the land-user's cognitive structures (i.e. internal behavior models), their functions may induce qualitative changes in human actions (e.g. triggering the adoption of new classes of farming technology or new farm types).

Observation includes performance indicators of the smallholder community in response to the configuration of system drivers; that is defined by the model users. Agronomic performance consists of crop production profit and returns to land and labor. Ecological performance includes nutrient balances for farm and soil. Economic performance is measured by net income, cash income, and net cash flow.

3.3 Sub-models

At the level of production units (i.e., soil, crop and livestock), the main sub-models are the functions of P availability in soil, soil loss by water erosion, crop and livestock yields. The function predicting P plant-availability (P_a) from total soil P (P_t) is drawn from the work of Dumas et al. [2011], which assumes a log-normal distribution for both P_a and P_t and expresses P plant-availability as a joint probability distribution for changes in both variables. Total soil P can be expressed as: $\boldsymbol{f_1(P_t^t) = f\left[P_t^{t-1} + \frac{1}{\rho D}\left(-x_{C_y}^{t-1} - x_{ma}^{t-1} + x_{eu}^{t-1} + x_{hw}^{t-1}\right)\right]}$; and plant-available soil P can be expressed as: $\boldsymbol{f_2(P_a^t) = \int (P_a^t|P_t^t)\, f(P_t^t) dP_t^t}$, where C_y is crop yield, ρ and D are respectively soil density and soil rooting depth. x_y^t is the P exported from the soil, per hectare; x_{eu}, x_{ma}, x_{re} and x_{hw} are P losses by soil erosion, P application rates of manure, plant residues and human waste in kgP/ha/yr, respectively.

Soil erosion is calculated using the standard Revised Universal Soil Loss Equation (RUSLE), meaning that soil loss is a function of rainfall, soil erodibility (of being soil type-specific), topography, and cultivation method and soil conservation measures.

Crop yield function predicts the crop yield response to P_a and other nutrient contents in soil, which is specific for soil and crop types based on regression analysis using either measured data, or data simulated by sophisticated crop growth models (linked to other studies). Livestock yield is calculated based on growth and reproduction rates of different livestock types.

At the farm level, the main sub-model is a Farm Agro-Economic Balance Accounting model (FAEBA sub-model) that calculates farm performance indicators based on interactions between farm production units (soil, crop and livestock). We formulated this sub-model utilizing the economic component of the Farm-NUTMON model [den Bosch et al. 1998a].

The decision-making sub-model of a household agent, named Nutrient Management Decision (NMD) sub-model, translates household profile variables, including its farm performance indicators, information from decision-outcome of other human agents, and information of external drivers (policy/programs, market, etc.) into household decisions about farm management. The dependent variables of the NMD sub-model include: (1) crop choices, (2) portfolio of fertilizer use (fertilizer types, quantity, frequency, application methods), (3) farm nutrient management practices to improve farm nutrient use efficiency and hence nutrient balance. We use the ordered choice algorithm (a form of bounded-rationality) presented by Le et al. [2008]. The algorithm includes the following main steps: (a) calculate choice probabilities for all alternatives (utility-maximization principle), (b) rank the choice probabilities in descending order, (c) randomly try the first choice probability in the ordered choice list. (d) If the probalistic try is successful, then the household chooses the corresponding choice, otherwise it will return to ordered choice list to pick the second alternative and repeat step to used labor/money allocated (c). This bounded optimisation holds the risk that some household agents select a nutrient management option that may not be the optimal alternative, but the chance for choosing the optimal is high.

The rule-based decision-making sub-model of the credit agent has two functions: (1) determining which farmers can borrow money under what conditions, and (2) deciding to change some important lending criteria (e.g. interest rate, loan duration and maximum loan amount) depends on its financial capacity, farmers' demand (at community level) and general economic status. Interactions between household and credit agents are reflected by the money flows between them.

5 DISCUSSION AND CONCLUSION

Although this study is still on-going, the presented model conceptualization and description already provide insights into the modeling of smallholder's P use and management to support multi-stakeholder discourse towards sustainable P use. Firstly, this is the first effort to clarify an MAS-based representation of the coupled HES underlying P use in smallholder communities that has a potential to capture social-ecological interactions across human and environmental hierarchies. Second, as the model is actor-oriented at multiple levels it is highly relevant for supporting nutrient management by key actors whose roles are already casted into the model.

Third, since the model mimics social-ecological feedback loops mediated by P flows and nutrient management practices it can help assess the non-linearity and trade-offs in the impacts of P use/recycling management options on the soil fertility, food production and household livelihood. Fourth, the representation of production units as autonomous agents helps capturing the influence of the structural diversity of the smallholder system on farm performance and resilience, which often is ignored in current nutrient dynamics models. Most importantly, our agent-based representation of human-induced feedback loop system (i.e. feedback loop structure is depending on agent's decisions) and heterogeneity in smallholder farms offers a high potential that help us understand better the systems' vulnerability and possible pathways for transitioning to resilience. Farming system's resilience arises from a rich structure of feedback loops - many of which mediated by nutrient cycles and farmer co-operations - that can work in different ways (e.g. one kicking in if another one fails) to restore the farming system after a large perturbation such as droughts and crises in the input prices. These design concepts and capabilities make MAPU model different from other integrated farm nutrient dynamics models, such as those developed by den Bosh [1998a,b] (static nutrient balance accounting), Shepherd and Soule [1998] (fixed structure of farm economic-nutrient dynamics) and Belcher et al. [2004] (aggregated land use - nutrient changes).

Finally, our strategy to develop one MAS model for the two contrasting P-use regimes helps improve the model robustness (i.e., less dependent on site-specific assumptions, more applicable to a wide range of contextual variation and management options, which are currently a critical limitation of many real-world MAS models). Indeed, the presented model conceptualization follows some generic ontology of smallholder farms in Southeast Asian rural, rather than a specific farm configuration in a particular area.

The high demands of data for system initialization, parameters' calibration and various validation tests required are the real challenges. However, our work has been supported by available tools and formalized disciplinary knowledge. For instance, the LUDAS model is close to MAPU. Well-represented components of farm nutrient flows and agronomic/economic farm performance in NUTMON model can be utilized. Validation tests will firstly focus on sub-models' validations, sensitivity, uncertainty and robustness analyses [e.g. Le et al. 2012], as well as the validation of predicted household behaviors using role-playing games [Barreteau et al. 2001].

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