Journal of Environmental Management 165 (2016) 298–312

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Non-hazardous pesticide concentrations in surface waters: An integrated approach simulating application thresholds and resulting farm income effects

M.A. Bannwarth [a, *], C. Grovermann [b], P. Schreinemachers [c], J. Ingwersen [a], M. Lamers [a], T. Berger [b], T. Streck [a]

[a] Institute of Soil Science and Land Evaluation, Biogeophysics Section, University of Hohenheim, Germany
[b] Department for Land Use Economics in the Tropics and Subtropics, University of Hohenheim, Germany
[c] AVRDC-The World Vegetable Center, P.O. Box 42, Shanhua, Tainan 74199, Taiwan

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
18 November 2014
Accepted 1 December 2014
Available online 1 October 2015

Keywords:
SWAT
MPMAS
Thailand
Environment
Eco-toxicological threshold
Impact assessment
Multi-agent system

ABSTRACT

Pesticide application rates are high and increasing in upland agricultural systems in Thailand producing vegetables, fruits and ornamental crops, leading to the pollution of stream water with pesticide residues. The objective of this study was to determine the maximum per hectare application rates of two widely used pesticides that would achieve non-hazardous pesticide concentrations in the stream water and to evaluate how farm household incomes would be affected if farmers complied with these restricted application rates. For this purpose we perform an integrated modeling approach of a hydrological solute transport model (the Soil and Water Assessment Tool, SWAT) and an agent-based farm decision model (Mathematical Programming-based Multi-Agent Systems, MPMAS). SWAT was used to simulate the pesticide fate and behavior. The model was calibrated to a 77 km^2 watershed in northern Thailand. The results show that to stay under a pre-defined eco-toxicological threshold, the current average application of chlorothalonil (0.80 kg/ha) and cypermethrin (0.53 kg/ha) would have to be reduced by 80% and 99%, respectively. The income effect of such reductions was simulated using MPMAS. The results suggest that if farm households complied with the application thresholds then their income would reduce by 17.3% in the case of chlorothalonil and by 38.3% in the case of cypermethrin. Less drastic income effects can be expected if methods of integrated pest management were more widely available. The novelty of this study is to combine two models from distinctive disciplines to evaluate pesticide reduction scenarios based on real-world data from a single study site.

1. Introduction

Agricultural land use is rapidly intensifying in mountainous areas of Southeast Asia. Until recently, the use of external inputs was rare, but where farmers have adopted high-value crops such as vegetables, fruits and cut flowers, synthetic pesticides are nowadays used widely and in large quantities (Schreinemachers et al., 2011). The rapid increase in the use of agricultural pesticides poses particular challenges for mountainous areas. There, farmers have little knowledge about the correct application of pesticides and the health risks they are exposed to. The spraying of pesticides on steep slopes, the high and intense rainfall under subtropical conditions, and the presence of well-developed preferential flow pathways result in a large share of pesticide residues being transported from the sites of application to lowland areas. This has the potential to affect a large population (Kahl et al., 2008; Duffner et al., 2012; Sangchan et al., 2012; Lamers et al., 2013).

The environmental risk can be reduced by decreasing pesticide applications, particularly in view of the fact that previous research has suggested significant overuse in northern Thailand (Grovermann et al., 2013). Nonetheless, the issue is contentious. Farmers are convinced that the pesticides they spray are essential, whereas the non-farm population feels that heavy pesticide use endangers their health and destroys the environment. This study therefore addresses the question how much current application amounts would have to decrease in order to achieve non-hazardous

* Corresponding author.
E-mail address: bannwart@uni-hohenheim.de (M.A. Bannwarth).

http://dx.doi.org/10.1016/j.jenvman.2014.12.001
0301-4797/

pesticide concentrations in stream water, while at the same time considering the effect of such reductions on farm incomes.

The relationship between application rates and surface water concentrations is complex and varies much over time and space. Reducing the average surface water concentration is insufficient because peak concentrations that might occur only seldom in a year are known to severely harm ecosystems (e.g. Satyavani et al., 2013). Intensive long-term monitoring and analyses would therefore be required, but might not provide enough data variation to statistically answer these questions. We therefore use simulation modeling as a virtual world to disentangle the relationships between pesticide application, stream concentrations and farmer incomes. In this context, pre-defined eco-toxicological threshold values are a scientifically grounded and practical instrument to specify pesticide use reduction scenarios for modeling.

The Soil and Water Assessment Tool (SWAT) is a semi-distributed hydrological model that simulates the water dynamics in a watershed, accounting for the spatial distribution of land use, soil and orography (Arnold et al., 1998). Previous studies have shown that SWAT is suitable to simulate the fate and behavior of pesticides (Bannwarth et al., 2014a,b; Larose et al., 2007; Boithias et al., 2011; Ficklin et al., 2012). Pesticide application rates are user-defined in SWAT and thus exogenous. SWAT does not model the effect of pesticide applications on crop yields. We therefore used another software tool, the Mathematical Programming-based Multi-Agent System (MPMAS) to assess the effect of alternative application levels on crop yields, land-use decisions and incomes (Berger, 2001; Schreinemachers and Berger, 2011). MPMAS belongs to a category of models referred to as agent-based models of land-use and land-cover change (ABM/LUCC). Such models typically combine a cellular component representing the physical landscape with an agent-based component representing human decision-making and interactions (Nolan et al., 2009). Different from most other agent-based models, MPMAS uses whole farm mathematical programming. The model has been widely used to ex-ante assess how changes in policies and technologies affect the livelihood outcomes of smallholder farmers in developing countries (Schreinemachers et al., 2007; Marohn et al., 2013), including Thailand (Schreinemachers et al., 2009, 2010).

The present study builds on previous impact assessments of pesticide use reduction (Falconer, 2000, 2001; Jacquet et al., 2011) by quantifying the change in farm household incomes in response to changes in pesticide applications. Falconer and Hodge (2000) developed a case-study farm model for the UK to evaluate low-input farming practices in combination with four distinct pesticide taxation and levy schemes. Linking an economic model to simulate decision-making about agricultural production with ecological indicators, they found significant trade-offs between economic and environmental objectives. The topic of pesticide use reduction policies was addressed by Jacquet et al. (2011) by means of an economic model at the national level for the French agricultural sector. Their study suggested considerable pesticide use reduction through taxation, but no evidence of significant income losses to farmers, as long as integrated farming techniques are widely adopted. Besides the reduction of pesticide pollution, the socioeconomic effects of reducing nutrient pollution caused by excessive fertilizer use have been assessed *ex-ante* with bio-economic modeling (Mimouni et al., 2000; Reidsma et al., 2012; Volk et al., 2008). Mimouni et al., (2000) used the Erosion-Productivity Impact Calculator in combination with a multi-objective mathematical programming model to evaluate trade-offs between farm income and lower levels of sediment and nitrate pollution. SWAT, among other hydrological models, was used by Volk et al. (2008) together with a representative farm model to examine the economic impact of ecologically defined pollution targets. Approaches integrating hydrological and economical models to assess water pollution abatement options are very rare in the literature. Harou et al. (2009) presented a comprehensive overview on the status of hydro-economical modeling, which showed that most research in this field focuses on assessing water allocation problems and infrastructure projects.

Our approach transcends previous studies because the economic impact assessment is based on eco-toxicological thresholds and simulated pesticide concentrations based on real-world data. This provides scenarios with scientifically grounded reduction targets. Moreover, we can better represent impacts at the farm level because the agent-based model takes into account resource endowments, land use practices and the livelihood strategies of a heterogeneous population of farm households.

We begin by presenting an overview of the input data, the two models applied in this study and how we integrated them. We then show the validation of both models and present the outcomes of reduced pesticide applications on pesticide concentrations and farm household incomes. Lastly, we evaluate and discuss the results given the inevitable uncertainties involved in each approach. We also propose alternatives to current pesticide application practices as well as measures to remediate farm income losses.

2. Material and methods

2.1. Study area

The study area is the Mae Sa watershed (Fig. 1), which covers 77 km^2 and is located 35 km northwest of Chiang Mai city in northern Thailand (18° 54′ N, 98° 54′ E). The watershed is drained by the Mae Sa River, which flows into the Ping River. The latter is a tributary of Thailand's main river, the Chao Praya. Prominent characteristics of the watershed are steep slopes; the average hill slope is 36%, but many slopes are steeper than 100%. Elevations range from 325 to 1540 m a.s.l. The main soil types are Acrisols and Cambisols with underlying granite, gneiss, freshwater limestone and marble. The area has a tropical wet and dry climate with a mean air temperature of 21 °C and total annual rainfall of 1250 mm. The wet period typically starts in May, the dry period in November.

Based on a land-use map derived from a SPOT 5 satellite image (GISTDA, 2007), about 24% of the watershed area is used for agriculture, while much of the remaining area is covered by deciduous and evergreen forest exhibiting various degrees of disturbance (Sangchan et al., 2013). Agriculture is highly diverse in terms of crops grown – a common feature of many upland areas in northern Thailand because the gradient of altitudes creates various microclimates suitable for different crops. The main crops are cabbages, kale, lettuce, bell pepper, tomato, chayote (*Sechium edule*), green bean, onion, chrysanthemum, roses, litchi as well as rice and maize. Many of these are high-value crops and farmers face considerable risks of losing these to pests. Therefore overall pesticide application rates have been estimated to be very high (13 kg/ha; Schreinemachers et al., 2011). Among the different categories of pesticides, insecticides were used most frequently (87% of farmers), followed by fungicides (68%) and herbicides (29%). For leafy and greenhouse vegetables, farmers drastically overuse pesticides and could increase their efficiency by reducing application amounts considerably (Grovermann et al., 2013). Pesticides are usually applied with handheld sprayers, and farmers use little or no protection, which creates substantial health hazards (Frenich et al., 2007).

2.2. Farm household survey

A structured questionnaire survey was conducted in the Mae Sa watershed in 2010. In each of the 12 villages practicing agriculture,