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An agent-based modeling framework for integrated pest management dissemination programs☆

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A B S T R A C T

The study of how people acquire and diffuse information among heterogeneous populations has a rich history in the social sciences. However, few approaches have been developed to better understand how information diffusion patterns and processes affect resource management in complex socio-ecological systems. This is a timely issue for crop protection diffusion programs, which have a larger place than ever on the international policy agenda due to the growing number of challenges related to controlling agricultural pests. To assess the impact of heterogeneous farmer behaviors (receptivity toward IPM practices) and types of information diffusion (either active or passive) on the success of integrated pest management (IPM) programs, we developed a socio-ecological model coupling a pest model (population growth and dispersion) with a farmer behavioral model (pest control and diffusion of pest management practices). The main objective of the model was to provide insights to explore effective IPM information diffusion strategies at the farmer community level. Our simulations revealed 1) that passive IPM information diffusion among agents seemed to be more effective to control pests over the community of agents than active diffusion and 2) that increasing levels of agent heterogeneity would significantly slow down pest control dynamics at the community level, but to a lower extent in the case of passive IPM information diffusion. Our findings therefore suggest that IPM diffusion programs should focus their efforts in developing methods to create purposefully the conditions for social learning as a deliberate pest control mechanism, while taking into account potential limitations related to the commonly reported farmer heterogeneity. Our study further stresses the need to develop a comprehensive and empirically based framework for linking the social and ecological disciplines across space and time in agricultural system management. While we specifically focus on pest infestation levels and IPM information diffusion strategies in this study, our approach to understand information diffusion within heterogeneous human populations in interaction with environmental features would be applicable to a much wider range of both social and resource management issues.

Software availability

Developer: F. Rebaudo
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Year first available: 2012
Software required: NetLogo 5.0 (Wilensky 1999)
Program language: NetLogo

The model description using the Overview, Design concepts and Details protocol (Grimm et al., 2010) can be found in Appendix A and the model itself in Appendix E (alternatively it can be obtained by contacting the authors). The model requires the Open Source multi-agent programmable modeling environment NetLogo which can be downloaded at http://ccl.northwestern.edu/netlogo/.

1. Introduction

Pest invasions can adversely affect agricultural practices and natural resources, imposing significant economic and environmental costs (Pimentel et al., 2005). While the probability of pest spread largely depends on the pest management options in place (Hashemi et al., 2009; Peshin and Dhawan, 2008), most spread models treat in detail the spatial aspects of the spread but lack the capability to incorporate the effect of control actions on further spread of the species (Cacho et al., 2010). Consequently, pest control strategies worldwide are generally based on the ecological

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characteristics of pest species or environment (Vuilleumier et al., 2011), and rarely consider the social environment in which pests spread (Carrasco et al., 2012; Khuroo et al., 2011; Larson et al., 2011). In the specific case of agricultural systems, the social environment is critical to understand pest spread as control actions mostly lie in the hand of farmers (either individuals or organized groups), whose behaviors have been shown to depend on a wide array of social (e.g. network structure) and ecological factors (e.g. pest dispersion) (Epanchin-Niell et al., 2010).

Worldwide, the lack of pest management competences is one of the main reasons why farmers fail to control pest attacks (Hashemi et al., 2009; Nyeko et al., 2002). This is especially true in the case of emergent invasive pests for which farmers have no pre-existing local knowledge and consequently have different perceptions and attitudes (García-Llorente et al., 2008). Over the past decades, extension science has developed several approaches toward farmers to promote pest control information diffusion (Van den Berg and Jiggins, 2007), including modeling techniques (Voinov and Bousquet, 2010). Information diffusion processes, based on theories of information dissemination (Brenner, 2006), can fit into two main categories, passive and active (Röling and Wagemakers, 1998). On the one hand, passive diffusion relies on the spread of pest control information and behaviors arising from innate mimicry among farmers (e.g. Collins, 2004). Fowler and Christakis (2010) have shown that behaviors can indeed cascade in human social networks even when people interact with strangers or when reciprocity is not possible; people mimic the behavior they observe and this mimicking can cause behaviors to spread from person to person to person (e.g. social learning *sensu* Bandura, 1977). On the other hand, active information diffusion relies on a spread of pest control information and behaviors arising from a limited number of farmers who train other farmers about pest control practices. This approach has been adopted by most participative integrated pest management (IPM) programs (e.g. farmer field schools, Van den Berg and Jiggins, 2007; Feder et al., 2004) and relies on the assumption that farmers may benefit training other farmers as it would prevent invasive pests present in the field of neighbors to re-infest their own fields. Both types of information diffusion have been classically observed in a wide array of agricultural situations (Schreinemachers and Berger, 2011; Feder and Savastano, 2006; Rogers, 2003; Berger, 2001).

Because behaviors and perceptions toward new information and technology can vary widely among farmers belonging to the same community (Dangles et al., 2010; Berger, 2001), farmers' behavioral heterogeneity is a key issue to understand and predict the success of pest control information diffusion throughout the community, and therefore the success of the IPM program at a large scale (Paredes, 2010). Moreover, farmers' decisions about whether to diffuse (or not) pest control practices from/to other farmers will be closely dependent on pest infestation in their own field (Peshin and Dhawan, 2008). This means that IPM information diffusion will be tightly linked to pest dynamics at the community level, itself depending on pest ecology and control behaviors of all farmers. The specification of IPM strategies in terms of the proportion of active vs. passive IPM information diffusion therefore requires the coupling of ecological and sociological models, an approach which has, to our knowledge, never been applied to IPM issues (Rebaudo and Dangles, 2011). In this context, agent-based models (ABM) may represent ideal tools to provide new theoretical insights into the sustainable development of farmers' control practices (Berger, 2001; Bousquet and Le Page, 2004; Liu et al., 2010; Smajgl et al., 2011). Although ABM have increasingly been applied to physical, biological, medical, social, and economic problems (Bagni et al., 2002; Bonabeau, 2002; Grimm et al., 2005; Freeman et al., 2009; Parrott et al., 2011) it has been, to our knowledge, disregarded by IPM theory and practice. The model developed here explored, via numerical simulations, the consequences of IPM strategies on pest population dynamics, under several assumptions regarding farmer behavioral heterogeneity (theoretical receptivity toward innovation) and farmer decision-making (short term benefits).

To explore theses strategies, we developed an ABM coupling a pest model to a behavioral model of farmer decisions. The pest model estimates pest population levels over time, while the behavioral model estimates IPM information diffusion from farmer to farmers. The behavioral model includes a social network range, which determines the possible interactions an agent can have with other agents and represents the environment in which information diffusion can occur (Choi et al., 2010; Kuandykov and Sokolov, 2010; Oreszczyn et al., 2010). Consequently, it would likely influence how IPM information would diffuse in the agricultural landscape. The pest model includes the pest dispersal rate, which determines indirectly the influence that one farmer pest control actions have on neighborhood farmers. If a farmer perceives the pest as a secondary threat (defined as a pest whose population rarely reaches intolerable levels), and if the pest has high dispersion capabilities, then lack of pest control would enhance infestation into the field of other farmers even if those other farmers apply control practices (Epanchin-Niell et al., 2010). In this complex system, pest infestation levels at the community scale emerge from the collective actions of IPM information diffusion and pest control among agents.

The general design of our ABM was determined from pest–landscape interactions, pest–farmer interactions, and inter-farmer interactions. In our model, pest control information diffuses among agents with heterogeneous behavior, and aggregate performance is measured as the mean pest infestation level over the community.

2. Material and methods

2.1. Model overview

Our socio-ecological model comprises three key elements: the agricultural landscape, the pest population, and the farmers (Fig. 1). The agricultural landscape represents a community of farmers composed of n farms, themselves divided into z fields. The whole community is therefore represented as a grid of $n \times z$ elementary cells (600 farmer's fields with $n = 100$ farms or agents) in which the pest disperses and becomes established following a cellular automaton process (see Rebaudo et al., 2011; Crespo-Pérez et al., 2011 for similar approaches). Pest dynamics were simulated through a logistic growth function (Verhulst, 1977), with pest dispersion occurring from one field to the Von Neumann neighborhood fields (see details in Appendix A). In each time step (equivalent to one pest generation) the infestation grew and spread over farms territories. To build our ABM we populated the agricultural landscape with n artificial agents, each of them representing a group of people working in the same farm (farm households as decision-making units, see Solano et al., 2006). In our model, agents attempted to control pest densities, and we assumed that their success in doing so was dependent on the IPM information they possess. A full description of the model is provided in Appendix A using the Overview, Design concepts, Details (ODD) protocol (Grimm et al., 2006, 2010).

In this study, we simulated a situation in which agents had no pre-existing knowledge to control the pest (as in the case of an emergent invasive pest), i.e. their initial level of IPM information $k = 0$ (with k ranging from 0 to 5, based on IPM information distribution characterized in a previous study, see Rebaudo and Dangles, 2011). We then assumed that y agents were trained to control the pest (simulating farmers trained through an extension program) and therefore set up the level of pest control of these agents to 5. We then carried out ABM simulations to assess the importance of two key social factors on the success of the IPM program at the community level: 1) the way the information acquired by trained agents diffused throughout the community and 2) the heterogeneity in individual agents' receptivity toward IPM practices.

2.2. IPM information diffusion

We compared two types of IPM information diffusion: 1) A passive diffusion in which agents mimic behaviors they observed from other agents having higher IPM information (and therefore better control practices), and causing behaviors to spread from agent to agent to agent. 2) An active diffusion (training) where agents