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A threshold area ratio of organic to conventional agriculture causes recurrent pathogen outbreaks in organic agriculture

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ABSTRACT

Conventional agriculture uses herbicides, pesticides, and chemical fertilizers that have the potential to pollute the surrounding land, air and water. Organic agriculture tries to avoid using these and promotes an environmentally friendly approach to agriculture. Instead of relying on herbicides, pesticides and chemical fertilizers, organic agriculture promotes a whole system approach to managing weeds, pests and nutrients, while regulating permitted amendments. In this paper, we consider the effect of increasing the total area of agricultural land under organic practices, against a background of conventional agriculture. We hypothesized that at a regional scale, organic agriculture plots benefit from existing in a background of conventional agriculture, that maintains low levels of pathogens through pesticide applications. We model pathogen dispersal with a diffusive logistic equation in which the growth/death rate is spatially heterogeneous. We find that if the ratio of the organic plots to conventional plots remains below a certain threshold l_c, the pest population is kept small. Above this threshold, the pest population in the organic plots grows rapidly. In this case, the area in organic agriculture will act as a source of pest to the surrounding region, and will always infect organic plots as they become more closely spaced. Repeated localized epidemics of pest outbreaks threaten global food security by reducing crop yields and increasing price volatility. We recommend that regional estimates of this threshold are necessary to manage the growth of organic agriculture region by region.

1. Introduction

A rapidly growing agricultural system is organic agriculture. This system has its origins in concerns over the accumulation of synthetic chemicals and the use of synthetic fertilizers in conventional agriculture, with harmful consequences to the environment (Trewavas, 2001; Ramesh et al., 2005; Carvalho, 2006; Hobbs, 2007; Badgley et al., 2007). Organic farming (Lampkin, 2007; Tamm, 2001) is gaining popularity in Europe, south America, north America, Japan and Australia among consumers and producers (OECD, 2008; Yussefi, 2004). These studies report an increase of 60% in global acreage under organic agriculture between 2000 and 2004, and an average annual growth rate of about 20%, although it reaches 50% in Turkey (Sayin et al., 2004). Initially supplied by numerous small operations, more recently large suppliers to international distributors have engaged in providing organic-labeled produce (Raynolds, 2004; Brand, 2006). Produce with an organic label meet the criteria that certify it was produced without applications of pesticides, herbicides, chemical fertilizers and free of genetically modified organisms, as governed by national or regional legislation. Consumers are drawn to these produce for two principal reasons. First, health conscious consumers perceive organic produce to be healthier (Woese et al., 1997; Yiridoe et al., 2005) and safer as they do not contain trace amounts of chemicals that are potentially hazardous to human health (Barceló and Hennion, 1997; Rivas et al., 1997; Sharpe, 1999). Second, organic produce are believed to be environmentally friendly, because organic agriculture avoids using chemicals that are perceived to be environmentally harmful to soil, freshwater, ground water and the air (Carvalho et al., 1997; Taylor et al., 2003; Chernyak et al., 1996). As many of these chemicals are not immediately biodegradable they can persist in the environment and bioaccumulate through the food web into many non-target species, including humans (Nhan et al., 1999; Carvalho, 2005). Two general concerns with organic agriculture are regularly raised. The first concerns food safety issues, the second is food security issues (Carvalho, 2006; Perfecto and Badgley, 2007). One would assume organic produce, having been produced without the application of pesticides would be safe to consume. However, there are regular recent cases of consumer illnesses and cross-border product recalls caused by contaminated organic produce, (US-FDA, accessed 31st March 2010). Thus, it is no longer possible to assume that organic produce are de facto safer than conventional produce. More significantly, the concern with food security is more difficult to address. Compared to

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conventional output, organic agriculture tends to produce statistically significant lower yields under intensive agriculture, due to decreased germination success and loss to disease, among other issues (Borlaug, 2000; Trewavas, 2002; Smil, 2000; Green et al., 2004). Can organically produced crops provide food security, while being more susceptible to yield fluctuations caused by pathogens and pests (Trewavas, 2001; Perfecto and Badgley, 2007)? The issue continues to be debated but it is clear that organic agriculture is more expensive (Ramesh et al., 2005). This becomes a more serious issue as more land under conventional agriculture is brought into organic production (Badgley et al., 2007).

In an agricultural landscape, organic farms operate against a background of conventional agriculture that maintains pathogen load and pest levels low. Intuitively, as the number of plots in organic agriculture increases they become closer together. Thus, as the number of plots in organic agriculture continues to increase, the number of refugia for pests and pathogens is postulated to increase. Therefore, it is worth considering whether disease outbreaks could become more frequent as the ratio of total agricultural land under organic farming increases relative to the area under conventional agriculture. We hypothesize that, in any given region, organic agriculture benefits from the conventional agriculture landscape which provides a low pathogen background. We further hypothesize that as organic agriculture plots become more frequent in the landscape, the likelihood of pathogen outbreaks increases. We addressed this question mathematically in one and two dimensions. The results show the existence of a bifurcation point above a threshold ratio of organic to conventionally farmed area, above which infections will always occur.

2. Theory and calculations

Typically, different mathematical modeling approaches are used to model agricultural pathogen dispersal at different scales (Maanen and Xu, 2003; Kuparinen et al., 2007; Viljanen-Rollinson et al., 2007). Many of the pests we wish to consider are spread by winds which have a prevalent direction. However, if we consider appropriate time and spatial scales, we can consider the direction of the wind to be close to uniformly random. On this scale, random diffusion is a reasonable assumption (Maanen and Xu, 2003; Kuparinen et al., 2007; Viljanen-Rollinson et al., 2007). For regional or descriptive models, one could include the effect of a dominant wind direction by adding an advective term. We focused on wind dispersed foliar pathogens and assumed that in organic plots pathogen control was less effective than in conventional plots.

In constructing the model, we make the following assumptions:

1. At the regional scale pathogens spread in a manner consistent with random diffusion.
2. In the absence of pesticide, the pathogen population is non-zero and can be modeled by a logistic growth model.
3. The addition of pesticide causes negative growth rate of pathogens and at sufficient concentration, it causes the population to die out.
4. In organic plots, positive growth rate of pathogens occurs because plot management does not independently prevent pathogen outbreak.

We now define the variables and parameters used in the model:

- p — The fraction of the maximal pest population
- D — The diffusivity of the pest
- ν — The rate of pest growth in the absence of pesticides
- μ — The death rate due to the presence of pesticide. We assume $\mu > \nu$ (assumption 3 of our model)
- l — The size of a farm plot devoted to organic practices
- and L — Size of the entire area

In one dimension, the model is then given by,

$$\frac{\partial p}{\partial t} = D\frac{\partial^2 p}{\partial x^2} + \nu p(1-p) - h_l(x)\mu p, \; 0 < x < L, \tag{1}$$

$$\frac{\partial p}{\partial x}(0) = \frac{\partial p}{\partial x}(L) = 0 \tag{2}$$

where,

$$h_l(x) = \begin{cases} 0, 0 < x < l \\ 1, l < x < L \end{cases}. \tag{3}$$

Here, $\frac{\partial^2 p}{\partial x^2}$ is the second partial derivative of p with respect to x and $\frac{\partial p}{\partial t}$ is the partial derivative of p with respect to time. This boundary condition allows us to consider infinite domains in which organic and conventional farms are interspersed periodically. By varying the value of l, we can examine the effects of varying the percentage of farmland devoted to organic methods. Note that related models were also considered in other contexts (Ludwig et al., 1979; Shigesada et al., 1986; Cantrel and Cosner, 1989; Berestycki et al., 2005) among others. Refer to the Appendix for the mathematical proof.

3. Results

The main result is that if l is sufficiently small, the pest population becomes extinct throughout the organic and conventional farms. However as the total area under organic farming l is increased, there exists a critical domain size of l_c such that if $l > l_c$ then there will be growth of pest in the organic farm which will then act as a source of pest to the neighboring agricultural region. In this case, the density of the pest is most concentrated within the organic area and decreases away from it (see Appendix A). The value of l_c is the smallest positive root of

$$\propto \tan(\propto l_c) = \beta \tanh(\beta(L - l_c)) \tag{4}$$

where $\alpha = \sqrt{v/D}$ and $\beta = \sqrt{(\mathrm{u} - \mathrm{v})/D}$.

In two dimensions the result is similar: as shown in the Appendix, pathogen outbreak will always occur if the area under organic farming is sufficiently large. For the special case when the organic area has a circular shape of radius l inside a larger conventionally farmed area of radius L, the critical threshold value l_c is given by

$$\alpha\frac{J_1(\alpha l_c)}{J_0(\alpha l_c)} = \beta\frac{K_1(\beta(l_c - L))}{K_0(\beta(l_c - L))}, \tag{5}$$

where J_i, K_i are Bessel functions of order i (Abramowitz and Stegun, 1964).

Mathematically, this behavior corresponds to a bifurcation of the zero steady state as l is increased past l_c. An example of this phenomenon is illustrated in Fig. 1 for $D = 1$, $\mu = 4$, $\nu = 1$ and $L = 10$. By numerically solving Eq. (4) we then find that $l_c = 1.047$. Fig. 1(a) shows $p(0)$ as a function of l. Note that a pest outbreak solution $p > 0$ bifurcates from the point $l = l_c$ as l is increased. The corresponding equilibrium profiles $p(x)$ are illustrated (Fig. 1b). Since there is a very large range of pest diffusivity in one direction, expressed from 10 m day^{-1} to 10,000 m day^{-1}, we plot the critical organic plot area l_c versus the logarithm of pest diffusivity (Fig. 2). From Eq. (4), it is clear that as $D \rightarrow \infty, l_c \rightarrow L\frac{\mu}{\mu + \nu}$. Therefore, from this simple relationship, one can estimate the critical ratio of organic to conventional farmed area for rapidly dispersing pathogens. A diversity of hypothetical scenarios demonstrates the critical threshold of organic to conventional area varies depending on the parameters (Table 1). In addition, this model can be refined further using local or regional scale models that contain more parameters if regional data exists.