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The dynamic biological relationship between insect pests and insecticide use: economic point of view and empirical evidence

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Insect pests are limiting factor in increasing agricultural productivity. Use of insecticides is one of alternatives, but the outcome is still unpredictable because of dynamic behavior of insect pests. Thus, basic knowledge about the relationship between insect pests and insecticide use in the agro-ecosystem is important. This study analysed the dynamic relationship between insect pests and insecticide use, which is built on an economic point of view. To see the relevance, this study utilized a data set on insect pest infestation and insecticide use in soybean based ecosystem. The study showed that, theoretically, there is a condition where level of insect pest infestation and effective insecticide use were partially stable, is not fully stable. Empirical evidence shows that the partially stable condition is not the case in soybean-based ecosystem. Total instability occurred, meaning that there will be pest explosion when the natural balance is disturbed. In this case, used insecticide was ineffective. The implication is that if the insect pest infestation tends to be uncontrollable, ecosystem of soybean should be halted and changed with other ecosystems.

Key words: insect pests, pesticides, biological linkage, dynamic model, soybean ecosystem

Introduction

Insect pests are one of constraints in agricultural production. It has been reported in many agrarian countries that insect pests have brought about considerable yield losses (Rola and Pingali, 1993). Therefore, Insect pests should be properly controlled in order to reach the potential production. Controlling insect pests is not an easy task, because of complexity in relationship between insect pest and their habitat. Naturally, pests have been controlled by natural enemies, such that the population levels of pests and natural enemies are in a balanced condition. But, because of interventions of human businesses, the natural balance of insect pests and natural enemies has been bothered. The used insecticide has been well considered an external factor disturbing the natural balance. Insecticides not only kill pests, but also kill

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beneficial organisms such as natural enemies and decomposers. Those organisms have been well identified as important components of agro-ecosystem (Settle *et al.*, 1996).

The relationship between insect pests and insecticide use exaggerates the complexity because of possibility of pests to be resistant to insecticides, as well as resurgence. Untung (1996) points out that insecticides have been known as cause of secondary pest outbreak in Indonesian rice agriculture during the 1970s and 1980s. An econometric study by Mariyono (2002) shows that insecticide use in rice is no longer effective in controlling multiple insect pests, even the insect pests significantly increased after application of insecticides. It has also identified that the relationship between insect pests and insecticides is in two ways after introduction of economic threshold concept in an integrated pest management strategy. In other hand, insect pests are dependent on insecticide use. On the other hand, insecticide use depends on the level of insect pests because insecticides are no longer used in scheduled manner (Mariyono, 2007; 2008).

It was observable that insect pests are naturally dynamic. The dynamics is affected by changes in agro-ecosystem, including insecticide use. Understanding the dynamics of insect pests and insecticide use makes it easier for farmer to manage insect pests below economically threshold level. This study aims to explore the dynamics of insect pests and insecticide use by using mathematical models. The economics theory underlines because, based on the facts the use of insecticide has a economic benefit. The dynamics of linkage between insect pests and insecticide use were derived from the economic theory. Empirical work takes a case of insect pests and insecticide use in soybean agro-ecosystem.

Theoretical framework

Since insecticides are used because of economic (profit) reasons, the underlying theory used in exploring the relationship between insect pests and insecticide use is micro-economics. Farmers face a problem of insect pests (a) that can reduce the potential value of output. The farmers use insecticides (x) to protect the potential output from losses associated with the insect pests. Thus, the farmers reach the potential production by maximizing yield that can be protected using insecticides. The farmers gained from the use of insecticides that protects yield losses associated with insect pests. However, using insecticides can not completely eliminate the insect pests, yield losses are still there. Have also case of migrations of pests coming from other places. So, the observable value gained by the farmer is formulated as:

$$v = h(x) + g(a) \qquad (1)$$

where $h(x)$ is a recovery function of insecticide use and $g(a)$ is a damage function of insect pests.

Biologically, insect pests grow at natural rates. In addition, the insect pests are suppressed by insecticide use. Thus, the evolution of insect pests over time can be expressed as:

$$\dot{a} = \psi + \alpha a + \delta x \qquad (2)$$

where $\dot{a} = {da}/{dt}$ is the rate of change in insect pests over time, ψ represents constant change in insect pests, α represents growth rate resulting from natural growth plus migration of insect pests, δ is a measure of impact of insecticide use on growth rate of insect pests. Note that if insecticide use is absent, insect pests will grow at α rate. In normal case, α is positive because population of insects increases, and δ is negative because insecticides kill insect pests. But, in a special case, the condition is reverse. When population of insect is very high, α could be negative. This condition is likely to happen when insecticides are no longer effective and insecticides cause pest resurgence, that is, δ is positive. An increase in use of insecticides leads to an increases in insect pests.

Based on the rationalization above, the dynamic relationship between insecticide use and insects pests can be derived from a lifetime problem of maximization faced by the farmers. The problem is mathematically formulated as:

$$\text{Max} \int_0^\infty \left(h(x) + g(a)\right) \cdot \mathrm{e}^{-\rho t} dt \qquad (3)$$

Subject to:

$$\dot{a} = \psi + \alpha a + \delta x \qquad (4)$$

$$a(0) = a_0 \qquad (5)$$

where $a(0) = a_0$ is the initial pest population and ρ is subjective discount factor. In this case, the use of insecticides is considered a control variable; and the insect pests are considered a state variable (Hoy et al., 2001). For empirical formulation, let denote $h(x) = \beta_0 x + \beta_1 x^2$ as a recovery function of insecticide use and $g(a) = \gamma \ln a$ as a damage function of insect pests. Note that β represents the property (or toxicity) of insecticides, and γ represents the virulence of insect pests. Under assumption of zero subjective discount factor, $\rho = 0,$ a Hamiltonian problem can be formulated as:

$$H = \beta_0 x + \beta_1 x^2 + \gamma \ln a + \lambda(\psi + \alpha a + \delta x) \tag{6}$$

The first order necessary conditions for maximization are:

$$\frac{\partial H}{\partial x} = \beta_0 + 2\beta_1 x + \lambda\delta = 0 \qquad \Leftrightarrow \qquad \lambda = -\frac{\beta_0}{\delta} - \frac{2\beta_1}{\delta} x \tag{7}$$

And $$\dot{\lambda} = -\frac{\partial H}{\partial a} = -\frac{\gamma}{a} + \alpha\lambda \tag{8}$$

Substituting λ of equation (7) into equation (8) gives:

$$\dot{\lambda} = -\frac{\gamma}{a} + \frac{\beta_0 \alpha}{\delta} + \frac{2\beta_1 \alpha}{\delta} x \tag{9}$$

Taking total differential equation (7), then differentiating with respect to *t* yields:

$$\dot{\lambda} = -\frac{2\beta_1}{\delta} \dot{x} \tag{10}$$

Substituting $\dot{\lambda}$ of equation (10) into equation (9) gives

$$\dot{x} = \frac{\delta\gamma}{2\beta_1 a} - \frac{\beta_0 \alpha}{2\beta_1} - \alpha x \tag{11}$$

So, there is a system equations resulting from the dynamic evolution of insect pests [equation (5)] and the dynamic evolution of insecticide use [equation (12)]. That is:

$$\begin{aligned} \dot{a} &= \psi + \alpha a - \delta x \\ \dot{x} &= \frac{\delta\gamma}{2\beta_1 a} - \frac{\beta_0 \alpha}{2\beta_1} - \alpha x \end{aligned} \tag{12}$$

This can be expressed in a matrix form of the first order partial derivative of the system can be expressed as:

$$\begin{bmatrix} \dot{a} \\ \dot{x} \end{bmatrix} = \begin{bmatrix} \alpha & -\delta \\ -\delta\gamma(2\beta_1)^{-1} a^{-2} & -\alpha \end{bmatrix} \cdot \begin{bmatrix} a \\ x \end{bmatrix} + \begin{bmatrix} \psi \\ \beta_0 (2\beta_1)^{-1} \end{bmatrix} \tag{13}$$

The determinant of squared matrix, $-(\alpha^2) - \delta^2 \gamma (2\beta)^{-1} a^{-2} < 0$, is negative, by mean that the system has a saddle path (Grafton *et al.*, 2004). This means that there is a path leading to the equilibrium point. Any point aside from the path will move away from the equilibrium. Diagrammatically, the canonical system in (13) can be expressed in a phase diagram, which is constructed step-by-step as follow.

At the steady state condition, there is no movement in a and x, meaning that $\dot{a} = 0$ and $\dot{x} = 0$ are respectively. These result in two isoclines associated with $\dot{a} = 0$ and $\dot{x} = 0$. First, draw an increasing isoclines for $\dot{a} = 0$ and a downward sloping isoclines for $\dot{x} = 0$ in a plane of a and x. Then identify the movements of a and x based on the model of the system equations. The direction of movements is expressed by an arrow. The model suggests that $\partial\dot{a}/\partial x < 0$, meaning that $\dot{a} < 0$ or a decreases $(\downarrow)$ when the level of insecticide use is greater than the level of which $\dot{a} = 0$ (above the isoclines for $\dot{a} = 0$); and $\dot{a} > 0$ or a increases $(\uparrow)$when the level of insecticide use is less than the level of which $\dot{a} = 0$ (below the isoclines for $\dot{a} = 0$). Likewise, the model suggest that $\partial\dot{x}/\partial x < 0$, meaning that $\dot{x} < 0$ or x decreases $(\leftarrow)$ when the level of insecticide use is greater than the level of which $\dot{x} = 0$ (above the isoclines for $\dot{x} = 0$); and $\dot{x} < 0$ or x increases $(\rightarrow)$ when the level of insecticide use is less than the value of which $\dot{x} = 0$ (below the isoclines for $\dot{x} = 0$). The motions of a and x are represented by the arrows on a plane of a and x. Any point away from both isoclines should move by following the resultant the arrows, called trajectories. The phase diagram is depicted in Fig. 1.

We can see that the system has a saddle point equilibrium. Beyond the equilibrium, the condition moves over time. There are two stories of which the maximum value is not the case. The first is that when insecticide use is getting higher, the level of insect pests is getting lower. This condition shows that farmers want to completely eliminate insect pests. The second is that the level of insect pests is increasing while the use of insecticides is decreasing. This is an indication that there is pest outbreak, and farmers no longer control the insect pests. In reality, both stories have been the case in Indonesian rice agriculture during the green revolution. High use of insecticides was addressed to maintain high production of rice. The use of insecticides was subsidized by the government (Barbier, 1989; Useem *et al*., 1992).

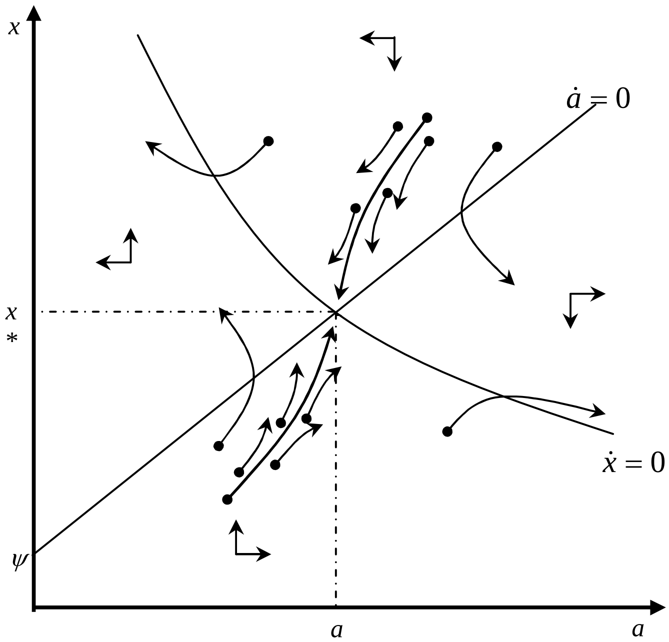

Fig. 1. Phase diagram of movements in insect pests and insecticide use

Empirical work

This part presents an evidence of the canonical systems of dynamic evolution of insect pests and insecticide use (equation (12)).
The system equations are modeled as:

$$\dot{a} = \phi_0 + \phi_1 a + \phi_2 x + \varepsilon \tag{14}$$

$$\dot{x} = \varphi_0 + \varphi_1 \frac{1}{a} + \varphi_2 x + \mu \tag{15}$$

where $\phi_0 \approx \psi$ is constant change in *a*, $\phi_1 \approx \varphi_2 \approx \alpha$ is growth rate of pest attack, $\phi_2 \approx \delta$ is rate of reduction in insect pests due to use of insecticides, $\varphi_0 \approx \frac{\beta_0 \alpha}{2\beta_1}$ are constant change in *x*, which is a non linear combination of toxicity of insecticide and growth rate of pest attack; $\varphi_1 \approx \frac{\delta\gamma}{2\beta_1}$ represents a nonlinear combination of pest virulence and insecticide toxicity; ε and μ are error terms.

Secondary time series data are employed in this work. The data comprises of four districts in the nine-year period from 1990 to 1998, when the data are well documented. The data come from a series of Annual Reports of Monitoring and Forecasting Pests and Diseases. The locations are four regions of Central Java, and the agro-ecosystem observed is soybean agriculture. Variables analyzed are insecticide use (kg) and intensity of insect pests in soybean agriculture (%) representing aggregate population of insect pests. Insects pests studied here consist of armyworms (*Spodoptera* spp.), pod worm (*Helicoverpa armigera*, Hubn), pod borer (*Etiella zinckenella*, Tr) and pod suckers (*Nezara viridulla*, L and *Riptortus linearis*, L). These pests are considered important soybean pests in Indonesia (Kalshoven, 1981). Farmers are assumed to face multiple insect pests and they have taken proper responses of controlling such pests.The equation (14) and (15) are estimated using a regression method called generalised least squared. The results are given in Table 1.

Table 1. Estimated system equation of insect pests and insecticide use.

	$\dot{a}$			$\dot{x}$		
	Coef.	**Sdt. error**	**z-ratio**	**Coef.**	**Sdt. error**	**z-ratio**
Constant	-358.96	124.50	-2.88^{b}	-267.53	102.05	-2.62^{b}
Insect pests, *a*	21.63	16.68	1.30^{c}			
1/insect pests, 1/*a*				0.1004	0.4456	0.23^{n}
Insecticide use, *x*	-0.5925	0.1873	-3.16^{a}	0.4395	0.1929	2.28^{b}
R^2	0.2736			0.1521		
Wald-test (χ^2)	10.92^{a}	p=0.0043		5.2^{c}	p=0.0742	
Observation	32			32		

Note: a) significant at 1% level, b) significant at 5% level, c) significant at 10% level, n) not significant.

	$\dot{a}$			$\dot{x}$		
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Note: a) significant at 1% level, b) significant at 5% level, c) significant at 10% level, n) not significant.

We can see that χ^2 of Wald-test in both equations are statistically significant. This implies that overall results are significantly estimated (Greene, 2003; Wooldridge, 2000). With respect to insect pests, we can say that insect pests grow over time, meaning that the population of insects increases. However, the population decreases as insecticide use increases. In this case, insecticides are still capable of diminishing insect pests. With respect to insecticide use, we can say that there is no effect of insect pests on insecticide use because the coefficient of 1/*a* is not significant. But, use of insecticides increases over time. These estimated results of system equations can be expressed as:

$$\dot{a} = -358.96 + 21.63 \cdot a - 0.5925 \cdot x \qquad (16)$$

$$\dot{x} = -267.53 + 0.4395 \cdot x \qquad (17)$$

By following the same procedure as before, at the steady state condition, set $\dot{a} = 0$ and $\dot{x} = 0$ are respectively. These result in two isoclines associated with $\dot{a} = 0$ is the increasing line, and $\dot{x} = 0$ is horizontal line. The isoclines for $\dot{x} = 0$ is horizontal because the coefficient of a in equation (15). The model suggests that $\partial \dot{a} / \partial x = -0.5925 < 0$, meaning that $\dot{a} < 0$ or a decreases $(\downarrow)$ when the level of insecticide use is greater than the level of which $\dot{a} = 0$ (above the isoclines for $\dot{a} = 0$); and $\dot{a} > 0$ or a increases $(\uparrow)$when the level of insecticide use is less than the level of which $\dot{a} = 0$ (below the isoclines for $\dot{a} = 0$). Likewise, the model suggest that $\partial \dot{x} / \partial x = 0.4395 > 0$, meaning that $\dot{x} > 0$ or x increases $(\rightarrow)$ when the level of insecticide use is greater than the level of which $\dot{x} = 0$ (above the isoclines for $\dot{x} = 0$); and $\dot{x} < 0$ or x decreases $(\leftarrow)$ when the level of insecticide use is less than the value of which $\dot{x} = 0$ (below the isoclines for $\dot{x} = 0$). The motions of a and x are represented by the trajectory of arrows on the plane of a and x. The systems can be expressed in a phase diagram in Fig. 2. Observal that the empirical dynamic system of insect pests and insecticide use in soybean agro-ecosystem is unstable. Any point aside the equilibrium were move way from the equilibrium point to four directions.

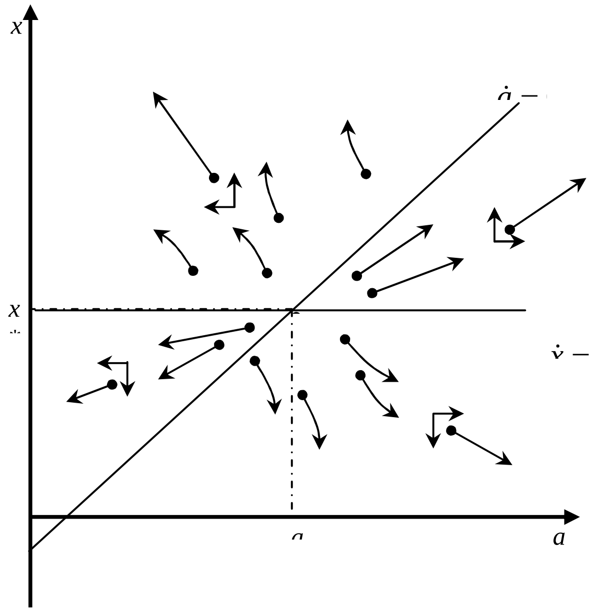

Fig. 2. Phase diagram of empirical movements in insect pests and insecticide use.

The most undesirable movement is that insecticide use and insect pests increase simultaneously, meaning that population of pests is getting higher when insecticides are used. Conversely, the most desirable movement is when insect pests and insecticide use are falling together. Two other movements are trade off, by means that if the insecticide use is high the population of insect pests is low and vice versa.

For theoretical justification of unstable condition, denote the empirically estimated dynamic system equations (16) and (17) represented in a matrix form as:

$$\begin{bmatrix} \dot{a} \\ \dot{x} \end{bmatrix} = \begin{bmatrix} 21.63 & -0.5925 \\ 0 & 0.4395 \end{bmatrix} \cdot \begin{bmatrix} a \\ x \end{bmatrix} + \begin{bmatrix} -358.96 \\ -267.35 \end{bmatrix} \qquad (16)$$

By following (Hoy *et al*., 2001) that the dynamic system equations will be unstable and diverges from steady state if the *eigen* values of the matrix are positive resulting from positive determinant of matrix, $(21.63 * 0.4395)$, and positive *trace* of matrix, $(21.63 + 0.4395)$. This means that if there is a shock disturbing of the system, the population of insect pests and insecticide use will move away from the steady state point, and never get back to the stable condition. If the most undesirable movement accidentally happens, farmers should terminate the system, and replace it with a new system. Applicably, in this case, soybean agro-ecosystem should be replaced with other agro eco-systems, for instance, maize and rice. Another alternative is to idle the eco-system or fallow the land.

Concluding remarks

By using a mathematical model derived from optimal control, the dynamic relation between insect pests and insecticide use in agro-ecosystem has been identified. Farmer needs to be careful in managing the agro-ecosystem since the dynamics of linkage between insect pests and insecticide use is not totally stable. If everything is under control, there is a saddle path leading to a steady state point which provides optimal level of insecticide use. The condition can be reached if the agro-ecosystem is managed correctly by wisely using insecticides. The steady state level of insect pests can be maintained at reasonably profitable level.

Empirically, the saddle point condition is not the case for soybean agro-ecosystem. For this area, the biological relation between insect pests and use of insecticides is unstable. There is a possibility for insect pest to be self-regulated, by mean that insect pests falls without any treatment from use of insecticides. Conversely, there is also a possibility for insect pests to be uncontrollable, by mean that insect pests can not be reduced using insecticides. If this is the case, the agro-ecosystem should be terminated, and start with a new agro-ecosystem.

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