An Integrated Ecological-Economic model for biological pest control

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1. Introduction

1.1 The need for objective monetary valuation of biodiversity losses

Biodiversity plays a key role in ecological processes and the delivery of ecosystem services, and its importance has been widely recognized (MA, 2005). In spite global actions, biodiversity is declining at an alarming rate (Butchart et al., 2012). In many cases, policy measures to safeguard biodiversity and resource developments are mutually exclusive and hence biodiversity conservation implies the decision to bear opportunity costs (Bennett et al., 2003). Being confronted with budget constraints, policy makers need to justify decision-making by supporting evidence of biodiversity benefits outweighing the opportunity costs incurred.

In 2001, the EU adopted the Biodiversity Action Plan, which aims at integrating environmental requirements into a market policy. In its mid-term assessment, the Commission confirmed the need for major action to stop the loss of biodiversity and acknowledged the need to strengthen independent scientific advice to global policy making (EC, 2008). But in spite the need for objectively comparable monetary standards to include biodiversity arguments in policymaking, the empirical literature investigating the relationship between species diversity and it's valuation from a farmers perspective is still scarce (Finger, 2015). On the one hand, the elicitation of values for biodiversity with the aid of stated preference methods is complicated due to the generally low level of awareness and understanding of what biodiversity means on the part of the general public (Christie et al., 2006). Furthermore, the willingness-to-pay (WTP) for species that are unfamiliar or undesired to the general public could yield extremely low values despite the fact that these species could be performing indispensible ecological services. On the other hand, revealed preference techniques have the advantage that they rely on the observation of peoples' actions in markets, however, the majority of species do not have a market price.

Therefore in this paper we introduce a methodological framework for the valuation of non-marketable species based on the ecological role of species in the agroecosystem to provide support for objective policy making outweighing the costs and benefits of biodiversity conservation. The framework integrates (i) a dynamic ecological model simulating interactions between species with (ii) an economic model integrating not only private costs but also external costs of a loss of species diversity. The model both (i) quantifies the contribution of biodiversity to the decrease in private and external costs in agroecosystems through the use of a production function technique, and (ii) attributes an objective monetary value to increased species diversity through the changes in the provisioning of a marketable good. The aim of the methodological framework is to provide quantifiable and objective measurements for the justification of biodiversity conservation through the delivery of verifiably comparable monetary standards which can be employed when considering trade-offs in policy making. The framework is applied for the presence of natural predators in pear production in Flanders (Belgium) and the results reveal the indirect use value of three non-marketable species which provide biological pest control for the pest insect pear psylla (*Cacopsylla pyri L.*) (Homoptera: Psyllidae).

1.2 Biological pest control for *Cacopsylla pyri* in organic and conventional pear production

Pear psylla is one of the key insect pests in European pear production (ref). The sucking psyllid causes damage on new branches and deformation of leaves, causing necrosis. The larvae produce honeydew leading to increased susceptibility for sooty mold, resulting in a blackening of the pear skin (ref). However, the literature quantifying the relationship between pest insect density levels and the occurrence of black pears is scarce (ref).

Already more than a decade ago, studies revealed the failure of conventional chemical control agents against the pear tree psyllid, stressing the need for alternative strategies such as enhancing natural arthropod enemies (Rieux et al., 1999). Integrated pest management (IPM) techniques combines appropriate measures from a range of pest control techniques including biological, cultural and chemical methods to suit the individual cropping systems (Tang et al., 2010). Visual scouting of the pest insect density, determines the appropriate levels of insecticide application. Alternatively, organic production is thought to favor natural enemies for crop protection purposes (Marliac et al., 2015).

2. Methodology

2.1 Methodological framework

The methodological framework that is applied here derives values for biodiversity based on the ecological role of the species within the ecosystem whereby a change in biodiversity impacts the provisioning of a marketable good. The approach consists of integrating a dynamic stock and flow ecological model with feedback loops to represent the interaction between species with an economic model which consists of a private (CBA) and social cost benefit analysis (SCBA). Two linking functions connect the ecological and the economic model.

The dynamic ecological model is based on a production function technique whereby the biophysical relationship between biodiversity and marketable goods in the production process are used to infer values for the inputs, even when they are not marketed. It forms an essential part of the framework, since it objectively quantifies the benefits of biodiversity to humans, as compared to stated preference techniques which reveal beliefs rather than the functional role of species within the agro-ecosystem. The economic model takes into account both (i) the private costs for farmers and (ii) the increase in external costs which are attributed to the reduction in species diversity. The results reveal the contribution of biodiversity to the increase in market value of agricultural outputs and its contribution is traced back throughout the ecological-economic model built and this way infers the value of natural predators throughout the production process.

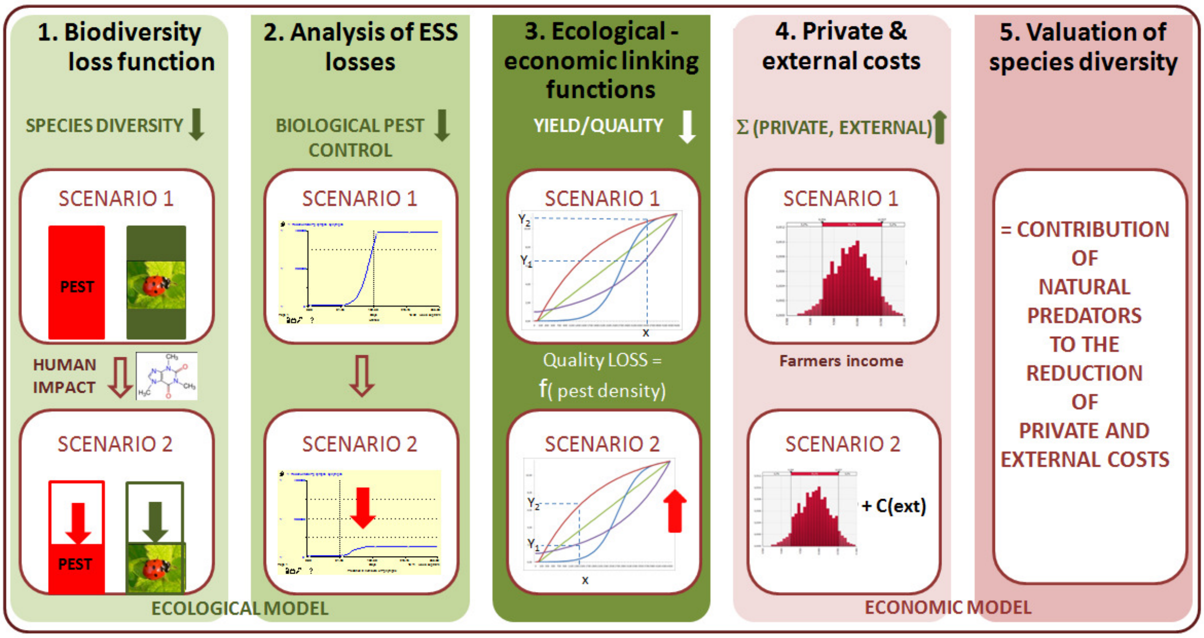


Figure 1: overview of the methodological framework with 1. The quantification of a biodiversity loss function for two scenarios (i) organic production and (ii) Integrated Pest Management (IPM). The loss of biodiversity in the IPM scenario is attributed to the application of insecticides; 2. The consequences of a reduction of biodiversity on ecosystem service delivery. The decrease in natural predators results in a decrease in the provisioning of the biological pest control service; 3. The first ecological-economic linking function links the density of the pest insect to the level of crop damage incurred. The second linking function links the level of pesticide use to the external costs encountered; 4. The economic model includes the private and external costs of the scenario with and without insecticide use; 5. The valuation of non-marketable species. The value of natural predators is retraced throughout the model and is defined as the contribution of natural predators to the reduction of private and external costs for marketable output production.

2.1 Ecological model construction

The ecological model simulates predator-prey dynamics between the pest insect and three of its main natural enemies under two different management scenarios: (i) organic production and (ii) integrated pest management (IPM). Organic production assumes the absence of the use of insecticides for the control of the pest insect, thereby revealing a higher number of natural predators due to the absence of collateral damage effects of insecticides on natural predators, as compared to the IPM scenario. First, a biodiversity loss function is calculated as the difference in species density levels for the two management scenarios. Second the loss in the ecosystem service biological pest control is quantified as the decrease in pest insects eliminated due to the reduction in the presence of natural predators.

2.1.1 Data collection

Each field test sampled pear psylla eggs and nymphs on multiple days with a maximum of ten The first dataset comprises a total number of 113 field tests in low strain *conférence* pear production (7 in organic production and 104 in IPM) on 15 different plots (8 in IPM and 7 in organic production) performed in Haspengouw (Belgium) for consecutive years of measurement (2004-2014). Data obtained from the plots under organic management were sampled in 2013 and 2014. Using the beating-tray method (3 beatings x 3 branches x 10 trees plot^{-1}), the nymph stages N1 to N5 are collected in a beating tray and counted (for a review of sampling methods see Jenser et al., 2010). A visual count is performed on newly developed shoot tips to assess the presence of eggs (visual counts are performed for 2 shoots per tree for 4-10 trees per plot segment with 4 plot segments per plot). Adult counts were performed sporadically with the beating-tray method but have not been included in the data due to its susceptibility to bias caused by adult mobility and the dependency on weather conditions. The mean counts of eggs per ten shoots are pooled for all consecutive years and plotted in figure 1.

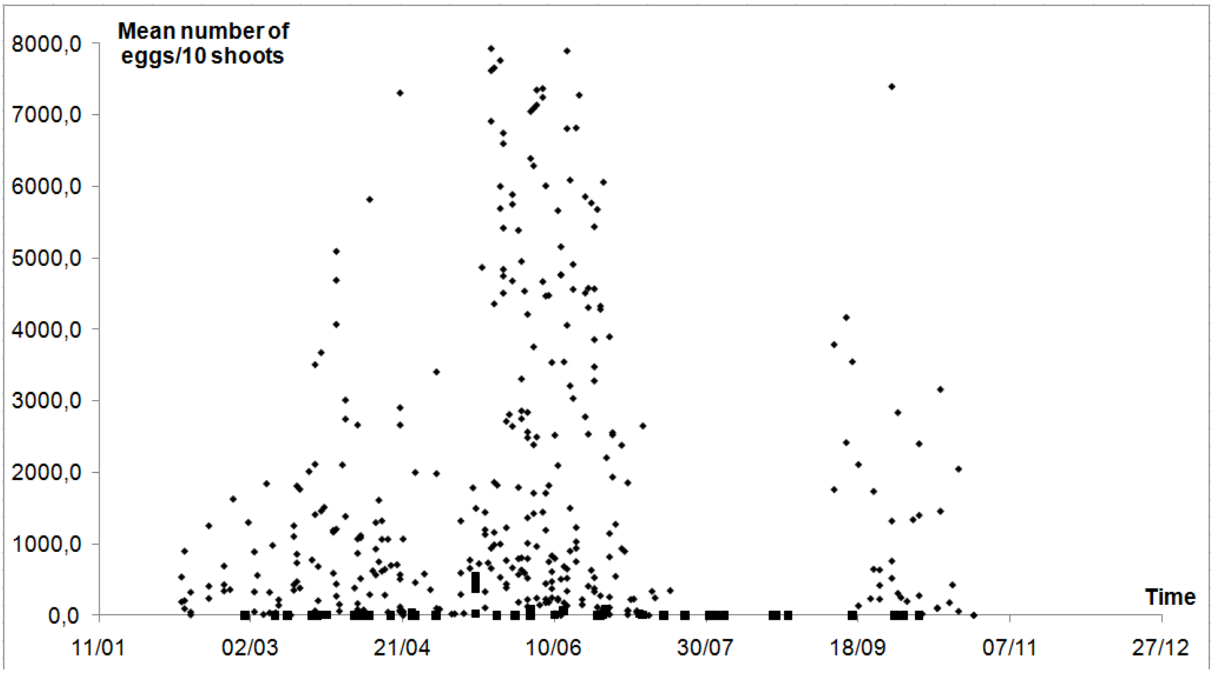


Figure 2: Pooled sample of mean numbers of pear psylla eggs per ten shoots collected between 2004 and 2014 (♦IPM; □ organic). Single fitted image.

In 2013 and 2014, counts for the presence of beneficial insects were been performed between February and Octobre in IPM and organic low strain *conference* pear plantations. Linear transects of three dug-in containers (r=0.2m) per 50m per pear row for three rows per plot were filled with water and detergent and left standing for 7 days. Emptying of the containers produced members of the order of the Aranea, Acari, Coleoptera, Hemiptera and Neuroptera. Figure 2 represents the pooled counts for a selection of the species in the samples collected based on the importance of their functional role as natural predators of pear psylla *Cacopsylla pyri* (Homoptera: psyliidae): *Anthocoris nemoralis* (Heteroptera: anthocoridae), *Allothrombidium fuliginosum* (Acari: trombidiidae) and *Heterotoma planicornis* (Hemiptera: miridae).

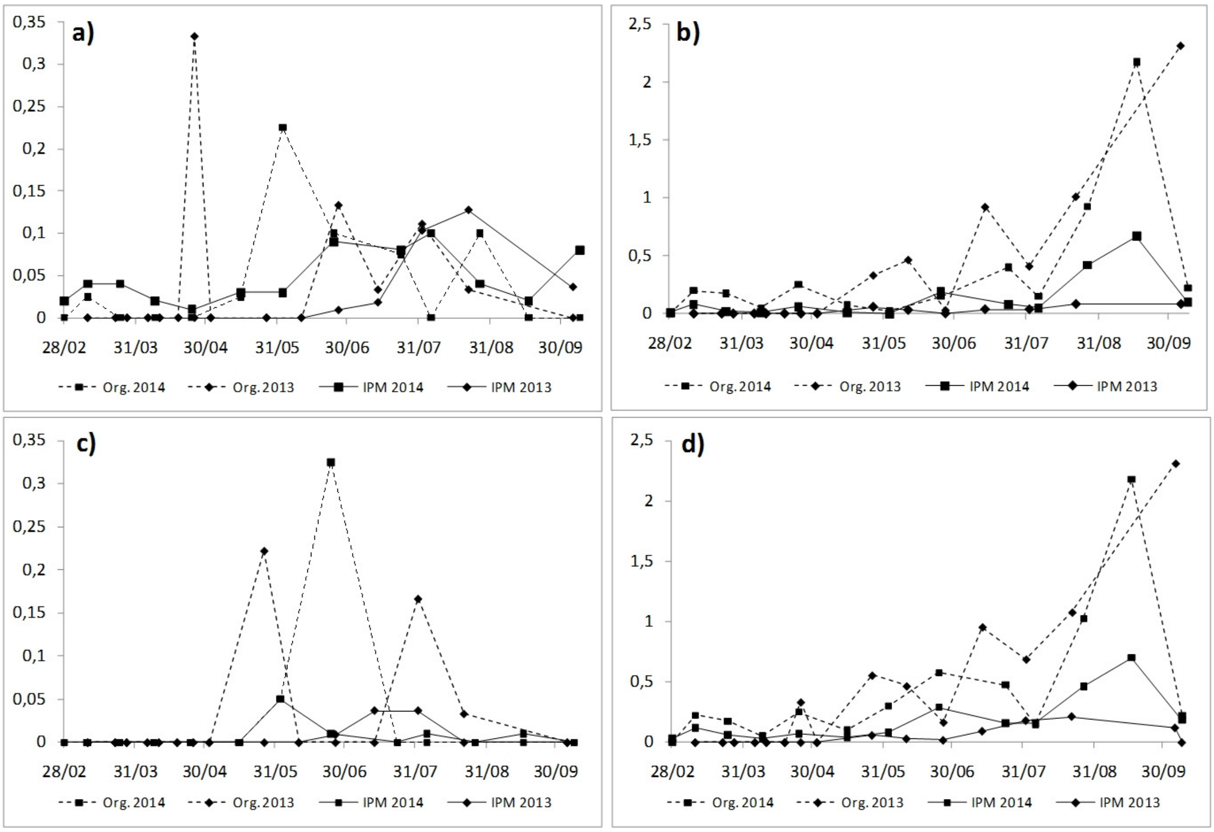


Figure 3: absolute number of individuals per sample for a) *Anthocoris nemoralis, b) Allothrombidium fuliginosum*, c) *Heterotoma planicornis* and d) sum of the absolute numbers of a, b and c. 2-column fitting image.

The second dataset was obtained from field test performed every two weeks for the period 2010-2011 on 14 plots (7 in organic production and 7 in IPM) in Hageland (Belgium) and Gelderland and Limburg (NL). The same techniques were used to assess mean egg numbers and larvae numbers (visual scouting and the beating tray method).

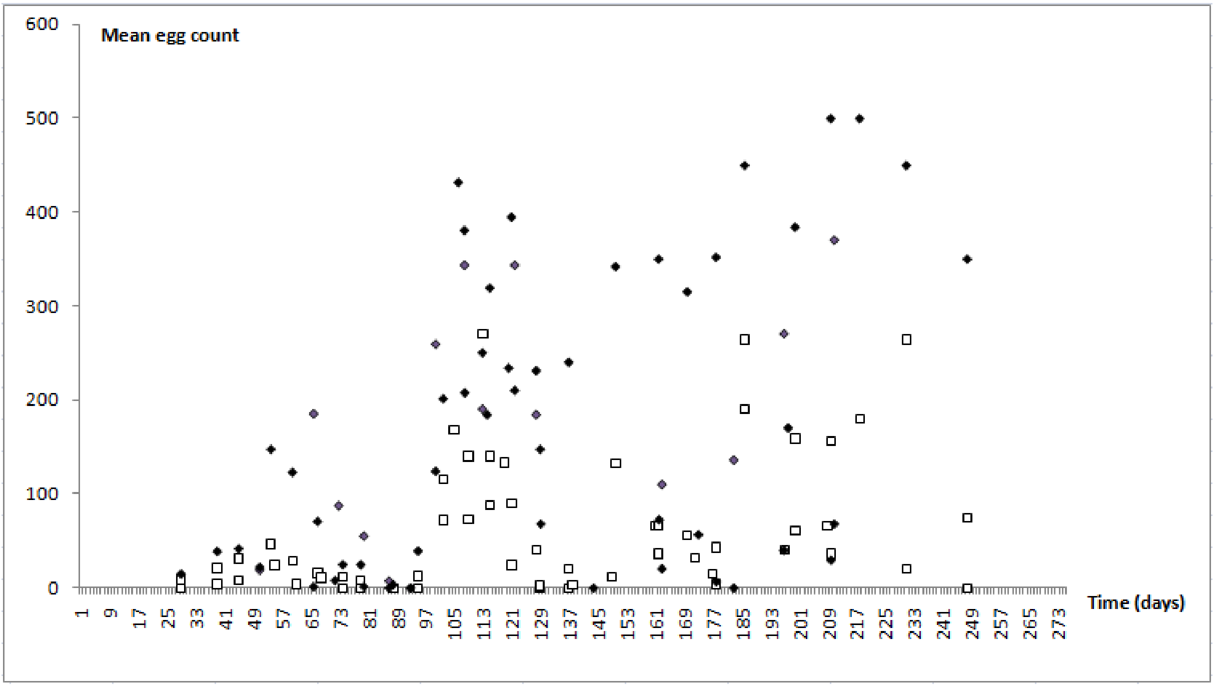


Figure 4: Pooled sample of mean numbers of pear psylla eggs per ten shoots (♦IPM; □ organic). Single fitted image.

2.1.2 Scenario 1: organic production (SCENorg)

In the reference scenario for organic production (ORG_1) the biodemographics of a pest insect *Cacopsylla pyri* (Pp) and the interaction with three of its main natural predators (i) *Anthocoris nemoralis* (An), (ii) *Allothrombidium fuliginosum* (Af) and (iii) *Heterotoma planicornis* (Hp) (Erler, 2004) are simulated over a period of one year whereby:

$$dN_{Pp}/dt = f\left(N_{An}, N_{Af}, N_{Hp}\right) \qquad \text{(eq. 1)}$$

with N = species abundance. With the use of stella 10.0.6 (Stella; available at http://www.iseesystems.com) (Costanza and Gottlieb, 1998; Costanza and Voinov, 2001), the population dynamics of the four interacting species are simulated simultaneously. The selection of species has been verified through expert opinion and literature reviews. The main criteria employed for inclusion in the model is the importance of the species as main pear psylla antagonists. The initial model parameter values are represented in table 1. All parameters are allowed to vary on a daily basis.

	Parameter	Model component	Initial value (resp.)
(1)	Intitalisation adults	Ppa, Ana, Afa	1.8 * 10^6; 29520; 0.41*10^6

(2)	Initialisation eggs	Hpe	$0.15 * 10^6$
(3)	Female fraction	Ppa, Ana, Afa, Hpa	0.5
(4)	Loss fraction (eggs)	Ppe, Ane, Afe, Hpe	0.3; 0.4; 0.65; 0.6
(5)	Pp Food fraction	Ann, Afn, Hpn, Ana, Afa, Hpa	0.8;0.8;0.2;0.2;0.2;0.2
(6)	Predation fraction	Ann, Afn, Hpn, Ana, Afa, Hpa	0.6

Table 5: Initial parameter values for Pp, An, Af, Hp for eggs (e), nymps (n) and adults (a)

The food fractions (the fraction that Pp makes up in the daily diet) has been set for specialists at 0.8 (An) and for generalists (Af and Hp) at 0.2. The number of Ppe and Ppn preyed upon per day are variable and depending on prey density according to a logistic dependancy. The higher the density of Pp, the more Pp will be subject to predation as opposed to a linear dependency approach. Ovipositioning and longevity are non-constant parameters, depending on the time of the year and the adult generation cycle. It is assumed that Pp growth is not constrained by the use of resources and does not reach carrying capacity. Due to both predator activity (and resp. insecticide application for the alternative scenario), the Pp population does not reach abundance levels which are high enough in order for resource use to become a constraint. The growth function is modeled as a logistic growth curve, followed by a decline of the population.

Throughout the model, the effects of omitted species in the agroecosystem have been taken into account in two ways:

(i) An, Af and Hp are prey to ommitted species and this effect has been taken into account by the inclusion of a predation fraction for An, Af and Hp of 0.6.

(ii) An, Af and Hp have multiple food sources besides Pp which is represented in the model by setting the An, Af and Hp food fractions to vary between 0 and 1. The predation fractions therefore allow the predation of ommitted species.

2.1.3 Model calibration

The field data reveals a large variability in both pest insect peak timing and maximum pest density over the years. It was opted to calibrate the simulation model for organic production based on field data from one year for which most datapoints were available (2010). The units of field measurements (mean eggs/10 shoots) were transformed to yield model parameter units (absolute egg numbers per hectare), based on expert judgement with 40 shoots/tree, 5% of the eggs captured and 1450 trees per hectare. The organic model seems to predict both the peak density as well as the timing of the peaks relatively well.

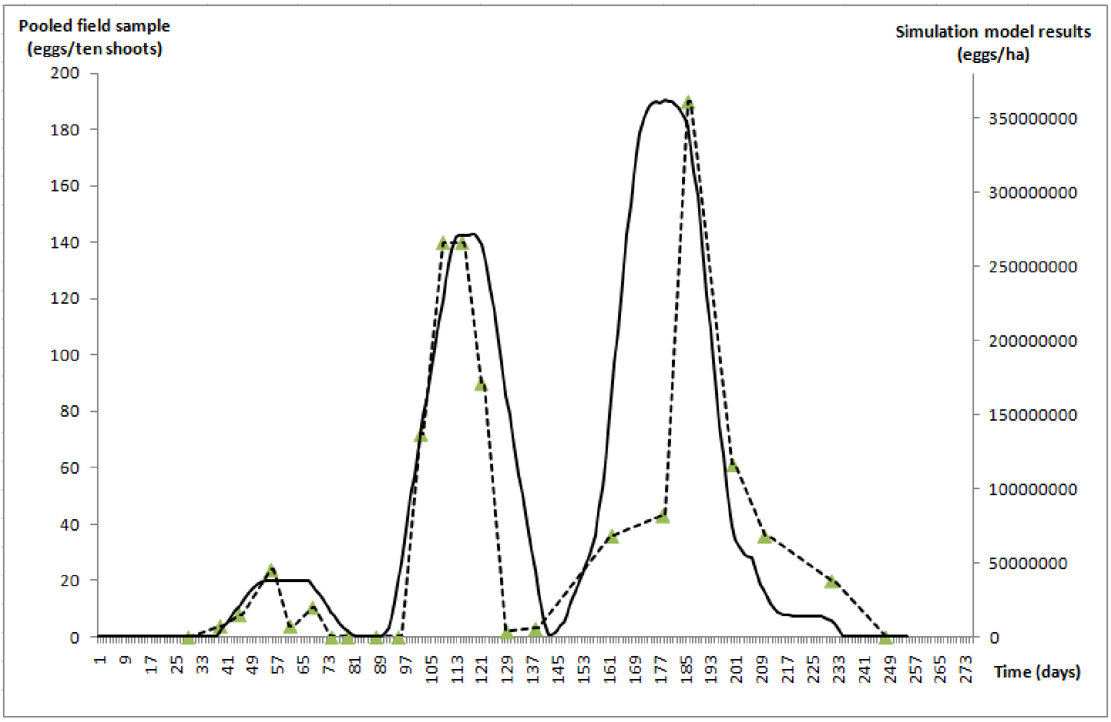


Figure 6: Model calibration for organic production based on field data from 2010, comparing the ppoled field sample (eggs/ten shoots) with the organic model results (eggs/ha) (- simulation model, -- field sample data). Single fitted image

2.1.4 Scenario 2: Integrated Pest Management (SCENipm)

In the reference scenario for Integrated Pesticide Management (IPM_1), the reference scenario for organic production is expanded with the introduction of insecticide applications. The timing (date), active ingredients applied and level of application (g/ha) are based on an exentensive dataset from 67 pear farmers over the period 2004-2014. The impact of consecutive insecticide applications (thiacloprid, Idoxacarb, fenoxycarb, spirodiclofen, abamectine, emamectine and rynaxypyr) is modeled as an immediate shock to the system, resulting in a death fraction as prescribed by ecotoxicological data.

Active ingredient	Pp_n	Pp_a	Af_n	Af_a	An_n	An_a	Hp_n	Hp_a
Thiacloprid	0.95	0.95	>0.75	>0.75	>0.75 *	>0.75 *	>0.75 *	>0.75 *
Indoxacarb	0.95	0.95	<0.25	<0.25	<0.25 *	<0.25 *	<0.25 *	<0.25 *
Fenoxycarb	0.95	0.95	0.5-0.75	<0.25	0.5-0.75 *	<0.25 *	0.5-0.75 *	<0.25 *
Spirodiclofen	0.95	0.95	0.25-0.5	<0.25	0.25-0.5 *	<0.25 *	0.25-0.5 *	<0.25 *
Abamectine	0.95	0.95	>0.75	>0.75	>0.75 *	>0.75 *	>0.75 *	>0.75 *
Emamectine	0.95	0.95	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *
Rynaxypyr	0.95	0.95	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *

Table 7: The ecological toxicity of active ingredients on An_n and An_a. (*) Data not available. For Emamectine and rynaxypyr, a safe level for death fractions of 0.25 is assumed. The effects on An_n and An_a are extrapolated to Af_n, Af_a, Hp_n and Hp_a.

For Pp, all insecticide applications result in an instantaneous death fraction of 95% of the population. For An, Af and Hp, death fractions applied are represented in table 2. The percentages assumed for emamectine and rynaxypyr are based on policy prescriptions requiring all insecticides used as ‘safe’ for the environment whereby ‘safe’ means that the collateral damage to beneficial organisms is 25% or less.

2.1.4 Biodiversity loss functions

The quantification of the loss of species diversity consists of analyzing two components: (i) loss in species richness which is defined as the loss in the total number of species present and (ii) the relative species abundance which describes how common the species is and is expressed in terms of absolute numbers per hectare.

Both for SCENorg and SCENipm, 6 alternative models are developed, each containing a different number of predators or a different combination of predators. Species richness is analysed by comparing the scenarios of SCENorg (resp. SCENipm) whereby each scenario contains a different number or combination of predators. Relative species abundance is analysed by comparing SCENorg with SCENipm scenarios since they contain the same species richness, but differ in terms of species abundance (e.g SCENorg1 and SCENipm1 both model 3 predators but the abundance for these predators in SCENipm is lower). Within both the organic management scenario (SCENorg) and the Integrated Pest Management scenario (SCENipm) different species richness levels are modelled for their effect on biological pest control. In doing so, the contribution of each of the individual species can be analysed, as well as the contribution of differing abundance levels (see table 8).

SCENorg							
Scenario	**Org_1**	**Org_2**	**Org_3**	**Org_4**	**Org_5**	**Org_6**	**Org_7**
Species number	4	3	3	3	2	2	2
Predator number	3	2	2	2	1	1	1
	⟹						⟹ (i)
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp
	⇕	⇕	⇕	⇕	⇕	⇕	⇕ (ii)

SCENipm							
Scenario	**IPM_1**	**IPM_2**	**IPM_3**	**IPM_4**	**IPM_5**	**IPM_6**	**IPM_7**
Species number	4	3	3	2	2	2	2
Predator number	3	2	2	2	1	1	1
	⟹						⟹ (i)
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp

Table 8: (i) Changes in species richness is modeled within scenario Org_1 to Org_7 (resp. IPM_1 to IPM_7), (ii) the difference in relative species abundance is quantified for scenario pairs ORG_1 and IPM_1 to ORG_7 and IPM_7.

(i) $$\% ORG_{within} = Pp(Org_x)/\ Pp(Org_1) * 100 \qquad \text{(eq. 2)}$$

(ii) $$\% IPM - ORG = Pp(IPM_x)/\ Pp(Org_x) * 100 \qquad \text{(eq. 3)}$$

(iii) $$\% IPM_{within} = Pp(IPM_x)/\ Pp(IPM_1) * 100 \qquad \text{(eq. 4)}$$

The model has not been constructed to allow for increases in natural predators abundance levels, when other natural predators competing for the same food source, decrease in numbers. Interdependancy between natural predators has not been modeled since the relationship between the pest insect and the natural predator is the main focus of the analysis and not the relationship between natural predators.

2.1.5 Quantification of biological pest control

With the aim of quantifying the biological pest control potential, the application of insecticides results in the decrease in the abundance of natural predators causing (i) a decrease in the number of pest insects consumed and (ii) an additional increase in pest insect abundance due to changing population dynamics. The relative loss of biological pest control (BPC) for Org_2 to Org_7, as compared to Org_1 is quantified as the sum of the increase I in the number of Pp_e and Pp_n and the decrease in Pp_e and Pp_n consumed C for a one-year period. Within SCENorg both the increase in Pp_e and Pp_n, as well as the decrease in Pp_e and Pp_n consumed are caused by a decrease in species richness for natural predators.

The sum of Pp_e, and Pp_n numbers is represented by $Pp_{en(x)}$. For all scenarios, the total biological pest control BPC_{tot} is equal to the total number of Pp consumed C_a

$$BPC_{tot} = C_a \tag{eq. 5}$$

The absolute loss in biological pest control BPC_{loss} for Org_2 to Org_7 as compared to Org1, is the sum of the increase Pp_I in the number of Pp_e and Pp_n and the decrease in Pp_e and Pp_n consumed C_{loss}

$$BPC_{loss} = \sum(C_{loss}, Pp_I) \text{ with} \tag{eq. 6}$$

$$C_{loss} = C_a - C_b \tag{eq. 7}$$

$$\text{and } Pp_I = Pp_b - Pp_b \tag{eq. 8}$$

The relative loss in biological pest control $BPC_{rel.loss}$for Org_2 to Org_7 as compared to Org1 is then

$$\frac{BPC_{loss}}{BPC_{tot\,(org1)}} \tag{eq. 9}$$

For the alternative scenarios within SCENipm, $Pp_I$is the result of both (i) a decrease in Pp_n due to the use of insecticides, as well as (ii) an increase in Pp_n and Pp_e due to the reduction in natural predators abundance levels as compared to the relevant SCENorg. For SCENorg, $PP_i = f\ (predators)$ whilst for SCENipm $PP_i = f\ (predators, insecticides)$

Therefore, the BPC_{tot} for the alternative SCENipm IPM_2 to IPM_7:

$$BPC_{tot} = \sum(C_{loss}, Pp_{predators}) \text{ with } C_{loss} = C_a - C_b \text{ and } Pp_{predators} = Pp_{insecticides} + Pp_I$$

$$\text{With } Pp_I = Pp_b - Pp_a \tag{eq. 10}$$

The difference in BPC_{tot} between SCENorg and SCENipm is quantified according to:

$${}^{BPC_{tot}ipm_x}\!/_{BPC_{tot}organic_x} \tag{eq. 11}$$

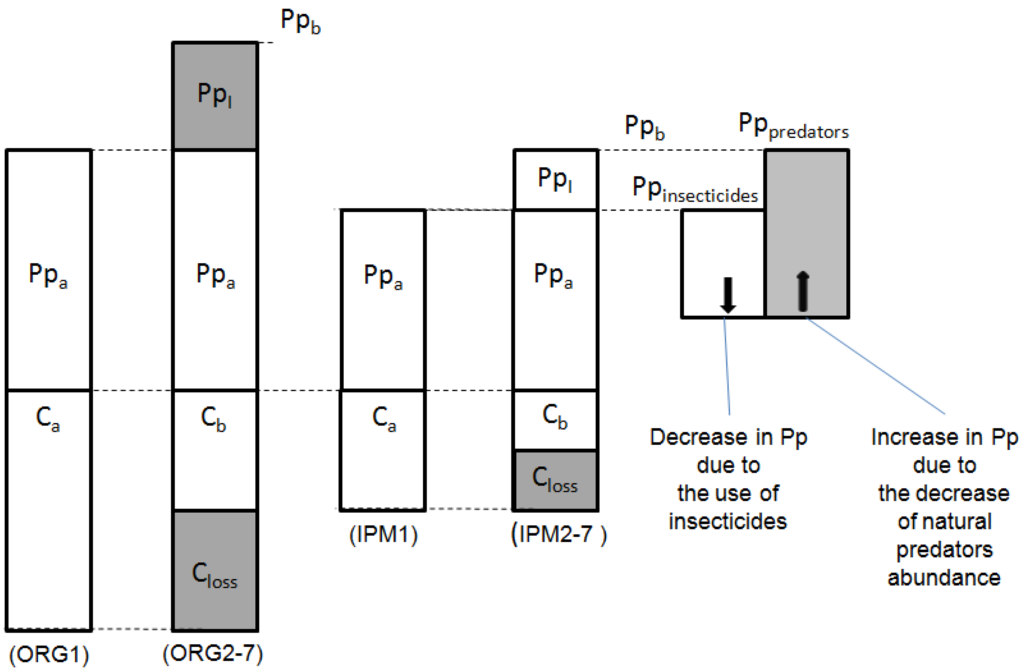


Figure 9: quantification of biological pest control for the reference scenarios (ORG$_1$ and IPM$_1$) and the alternative scenarios

2.3 Economic model construction

The economic model integrates not only private costs but also external costs of a loss of species diversity. The model both (i) quantifies the contribution of biodiversity to the decrease in private and external costs in agro-ecosystems through the use of a production function technique, and (ii) attributes an objective monetary value to increased species diversity through the changes in the provisioning of a marketable good.

2.3.1 Data collection

Annual accounting data on yields (kgha^{-1}), benefits (€ha^{-1}), variable costs and fixed costs at farm level for 22 pear farmers employing IPM during the period 2010-2013 were put at our disposal by the farming union. Averages and standard deviations were calculated. Accounting data for organic production were assumed equal to IPM for all parameters but (i) yield of fruit for consumption including 1st class, 2nd class and non-consumable pears (kgha^{-1}), (ii) cost for crop protection, (iii) full-time equivalents (FTEs) for labour (eg. no manual weeding), (iv) subsidies and (v) selling prices (€kg^{-1}) (EC, 2013). Furthermore, percentages of black pears for SCENorg and SCENipm were allowed to vary according to maximum pest insect density (see section 2.4.1). It is assumed that organic yields equal 80% of IPM yields but higher selling prices for organic products make up for lower yields (EC,

2013) with $\mu_{(IPM)}$ =34800 kgha^{-1} and $\mu_{(org)}$= 27850 kgha^{-1}, $P_{(IPM)}$ = 0.70 €kg^{-1} and $P_{(org)}$= 0.88 €kg^{-1}. Crop protection accounts for an average of 1600 €ha^{-1} and no costs for chemical crop protection is taken into account for SCENorg. Subsidies for SCENipm (resp. SCENorg) averaged 140 €ha^{-1} (resp. 210 €ha^{-1}) (Departement Landbouw en Visserij; 2014). Organic farming is more labour intensive requiring more FTEs on a per hectare basis with average costs for seasonal workers for SCENipm (resp. SCENorg) 4200 €ha^{-1} (resp. 5400 €ha^{-1}) (EC, 2013) (See ANNEX A.)

2.3.2 Private cost model

The economic model assesses (i) the private costs for SCENorg and SCENipm and (ii) the external costs incurred through the use of insecticides for SCENipm. The private profit maximization function is based on the damage control model for responsive applications by Lichtenberg and Zilberman (1986a) and is here defined as:

$$Max \prod_{p} = pg(Z)\int_{N1}^{N2}\left[1 - D\big(N, X(N), P(X)\big)\right]\varphi(N)dN - \omega\int_{N1}^{N2} X(N)\,\varphi(N)dN - \tau Z(management) - m$$

(eq. 12)

The benefits are represented by the output price p multiplied by the realised yield $g(Z)$ whereby the yield damage D is a function of the pest population density N, the amount of insecticides applied $X(N)$ and the natural predator density $P(X)$. The private costs encountered are the costs τ with regards to input factors (labour and capital) Z, the cost of pesticide use ω which varies depending on the amount of pesticides applied $X(N)$ depending on the pest density level N_1 to N_2, and monitoring costs m. (For a full description see Lichtenberg and Zilberman, 1986a).

The effect of increased natural predator richness and relative natural predator abundance results in a decrease of pest density levels, causing a decrease in the level of insecticides required under responsive applications management. Lowering the amount of insecticides applied consequently lowers the external costs borne by society and rendering additional value to the presence of increased natural predators richness and abundance. Therefore, the Lichtenberg and Zilberman model is expanded with an inclusion of the external costs C_{ext} to take into account the monetary value of the impact of insecticides on human health and the environment.

$$C_{ext} = \vartheta \int_{X1}^{X2} C_{ext}\, \varphi(N) dN \qquad \text{(eq. 13)}$$

with ϑ the quantity of pesticides used and C_{ext} the aggregated cost per unit of insecticides on human health and environment, varying for differing levels of pesticide use X_1 and X_2.

The social profit maximization function therefore becomes:

$$Max \prod_{p} = pg(Z) \int_{N1}^{N2} \left[1 - D\big(N, X(N), P(X)\big)\right] \varphi(N) dN - \omega \int_{N1}^{N2} X(N)\, \varphi(N) dN - \vartheta \int_{X1}^{X2} C_{ext}\, \varphi(N) dN$$
$$- \mu Z(management) - m$$

(eq. 14)

In the private cost model, the effect of the potential differences in the occurrence of black pears is analysed for its impact on (i) gross income and (ii) farm income.

The gross income I_G is defined as:

$I_G = \sum(I_b, I_r)$ (eq. 15)

where $I_b$represents the gross income from black pears:

$I_b = P_b * Q_b$ with $P_b$the price of black pears and Q_b the quantity of black pears (eq. 16)

and I_r the gross income of regular pears

$I_r = P_r * Q_r$ with $P_b$the price of black pears and Q_b the quantity of black pears (eq. 17)

The farm income is defined as

$I_F = I_G - TC$ (eq. 18)

with $TC = \sum(C_v, C_f)$ and TC the total costs, C_v the sum of the variable costs and $C_f$the sum of all fixed costs.

The accounting data are imported into the risk analysis tool Aramis (@risk) and all variables are allowed to vary in order to calculate a confidence interval for the farm income for all SCENorg and SCENipm.

2.3.3 External cost model

The presence of natural enemies reduces the number of pest insects, and therefore also reduces the amount of insecticides which needs to be applied. Hence, the presence of natural predators indirectly reduces the external costs associated with the use of pesticides. A large number of surveys have been published, revealing the external costs to society of pesticide application (Pimentel et al., 1993), eg. the effects of pesticide application on public health, groundwater contamination, and fishery losses. However, for this analysis it is not the total effect of all pesticides used that is modeled and therefore the link between external costs and the level and use of specific insecticides is analyzed through the use of the pesticide environmental accounting tool (Leach and Mumford, 2008). The tool calculates the total economic costs of a specific insecticide applied taking into account the effect on farm workers (applicators and pickers), consumers (ground water leaching and food consumption) and the environment (aquatic life, bees and birds).

2.4 Constructing an integrated dynamic ecological-economic model

Linking the ecological model with the economic model is established by two linking functions: (i) the damage threshold function that links the pest density level with the yield quality decrease and (ii) the pesticide environmental accounting function relates the use of insecticides with the of external costs to society (e.g. impacts on human health and environment).

2.4.1 Damage threshold function

The presence of the pest insect induces the presence of a sooty mold which becomes visible on the pears as a blackening of the skin, rendering them less valuable when sold on the market. Linking the density level of the pest insect with the economic damage it causes or, linking the biological pest control provided by the presence of natural predators with the economic costs avoided, requires analyzing the relationship between pest insect density and the reduction in quality. The damage control function links the density of the pest insect (adult days/ha) to the yield loss (% black pears occuring). As a general guideline it is recommended by governmental authorities that when monitoring the pest insect reveals a density which is larger than 1000 adults per 10 beatings, action (insecticide application) is allowed because a not further specified 'detectable damage' will be incurred. Recalculating 1000 adults per 10 beatings into numbers per ha results in the presence of a minimum of 386*10^6 adults/ha yield to yield 'detectable damage'. Since it is assumed that farmers are maximizing profits, 'detectable damage' is translated into the lowest amount of black pears that is desired (<1%). Fixating this value at 1% equally fixes the maximum percentage of black pears (at maximum pest density). Therefore a second damage threshold function (high impact damage function) is constructed for which the maximum percentage of black pears obtainable is 100%. Since the shape of the damage control function is not known, four hypothesized relationships were constructed to simulate the correlation between Pp_a density levels δ_{ppa} ($ha^{-1}y^{-1}$) and black pear occurrence γ (%):

(i) Linear: $\gamma_{lin} = \alpha\, \partial_{Ppa}$ with $\alpha = 0.0026$ (eq. 19)

(ii) Logistic: $\gamma_S = \frac{k}{(1+(k-\partial_0/\partial_0)} * exp^{r\partial_{Ppa}}$ (eq. 20)

with k (stable value) = 11.66 (max of the linear function), ∂_0(initial value) = 0.01 and r (rate) = $k/\mathrm{max}_{\partial \mathrm{ppa}}$ and $max_{\partial ppa}$ = 4500

(iii) Logarithm: $\gamma_{log} = 1 - exp^{-\partial_{ppa}}$ (eq. 21)

(iv) Exponential: $\gamma_{exp} = exp^{\partial_{ppa}}$ (eq. 22)

This results in a lower bound γ_l and upper bound γ_u for both the low impact model and high impact model for all SCENorg and SCENipm with:

$\gamma_l = \min\,(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp})$ and $\gamma_u = \max\,(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp})$ (eq. 23)

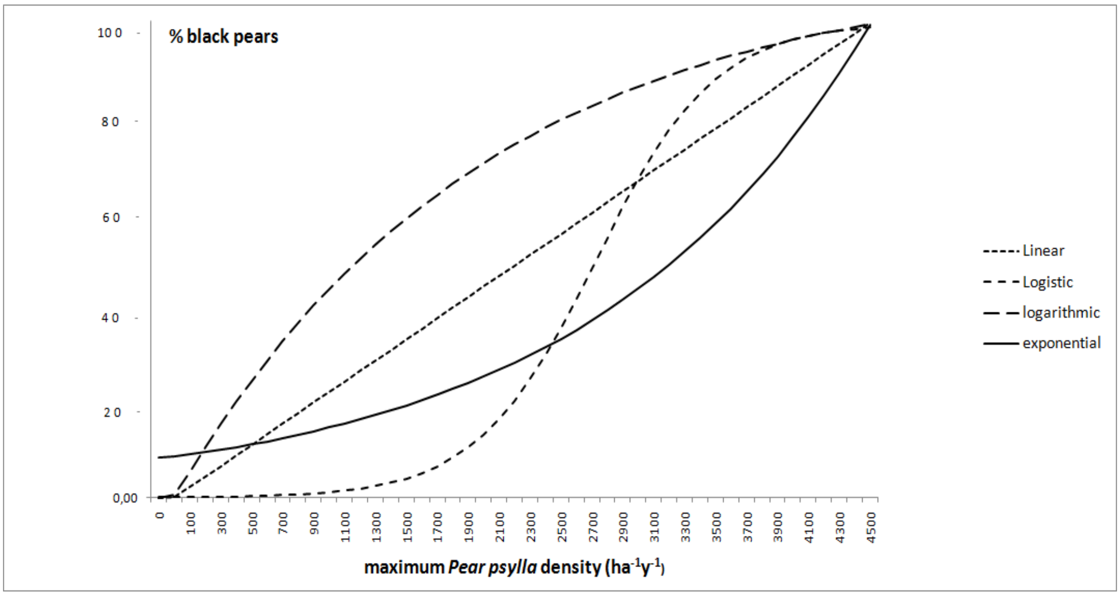


Figure 10: (Low impact damage function). The damage threshold function relates the maximum Pp density which is observed to the percentage of black pears that could be expected, based on four hypothesized correlations (a) linear, (b) logistic, (c) logarithmic and (d) exponential.

3. Results

3.1 Species richness and relative species abundance

The effect of consecutive insecticide applications on species abundance for Pp in SCENIPM1 as compared to SCENORG1 reveals an overall decrease in abundance of 45.73 % (table 10). A significant decrease in pest numbers was expected. The population dynamics of Ppe, Ppn, Ppa, Afa, Ana and Afa for SCENorg1 (left) and SCENipm1 (right) are represented in figure 9.

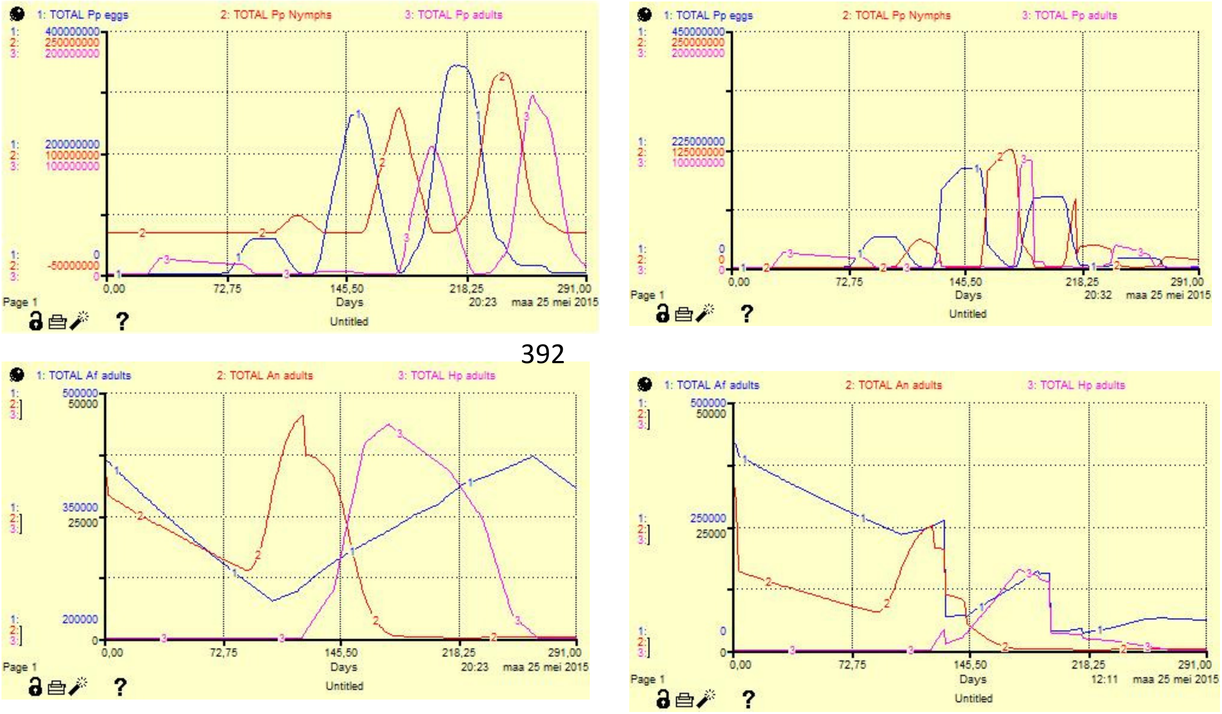


Figure 11: shows the number of individuals for a one year period for SCENORG1 (left hand side) and SCENIPM1 (right hand side). Top left (resp. right): numbers of pear psylla eggs (blue), nymphs (orange) and adults (pink). Bottom left (resp. right) population dynamics for Af adults (blue), An adults (red) and Hp adults (pink). The sharp decreases in population numbers in the bottom right graph are due to the application of insecticides at that time.

The reduction in the species richness of natural predators for SCENorg1 to SCENorg7 reveals an increase in Pp adult numbers with a factor to 2.06 to 19.31 according to equation (2). Due to the use of insecticides the difference between SCENorg$_x$ and SCENipm$_x$ for the same natural predator species richness results in losses between 45.73 % and 95.34% according to equation (3). The % increases in Pp for SCENipm remain within a narrower range of between factor 1 and 2.78 according to equation (4).

SCENORG	Org$_1$	Org$_2$	Org$_3$	Org$_4$	Org$_5$	Org$_6$	Org$_7$
Species richness	4	3	3	3	2	2	2
Predator richness	3	2	2	2	1	1	1
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp
Pp (x 10^6)	1237	2551	8130	12633	10905	16005	23888
% ORG$_{within}$		206	657	1021	882	1294	1931

SCENIPM	IPM$_1$	IPM$_2$	IPM$_3$	IPM$_4$	IPM$_5$	IPM$_6$	IPM$_7$
Species richness	4	3	3	2	2	2	2
Predator richness	3	2	2	2	1	1	1
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp
Pp (x 10^6)	671	671	791	1623	791	746	1872
% IPM-ORG	-45.73	-73.68	-90.27	-87.16	-92.75	-95.34	-92.16
% IPM$_{within}$		100.00	117.79	241.69	117.79	111.16	278.78

Table12: (upper) Increases in Pp adult abundance due to the reduction in natural predators species richness, (lower) Decreases in Pp adult abundance due to insecticide use.

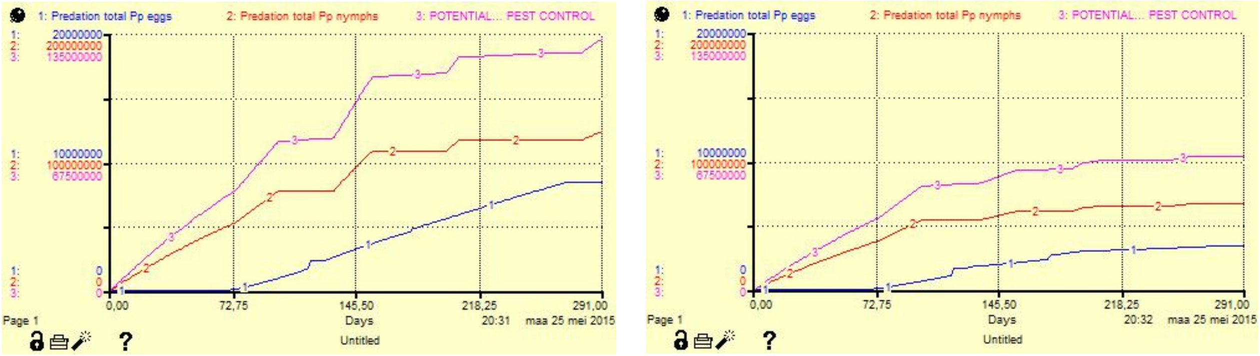
Species abundance levels for natural predators in SCENIPM1 decrease significantly. The decrease in total numbers of each predator ranges between 20.44% (Hp) and 45.31 % (An) (table 13).

	SCENORG	SCENIPM	% loss
An	99731	54540	45.31
Af	1216022	763853	37.18
Hp	145316	115611	20.44

<u>Table13:</u> Losses in relative species abundance for natural predators for SCENoprg as compared to SCENipm (death rates according to table 5)

3.2 Biological pest control (BPC) losses

A cumulative graph of BPC_{tot} for SCENorg1 as compared to SCENipm1 shows a substantial difference between biological pest control under organic management as compared to IPM. Results reveal that for the loss of the first predator, the BPC_{tot} of IPM management drops to between 0.71% and 75.02% as compared to organic management, and to between 7.54% and 84.87% with the loss of the second predator.



<u>Figure 14:</u> total number of pest insect nymphs removed by natural predators for the reference scenario (a) and the alternative scenario (b) for a period of one year

SCENipm	**Pred.**	**$BPC_{totorg(x)}/BPC_{totipm(x)}$**
IPM1/ORG1	3	52.60
IPM2/ORG2	2	61.46
IPM3/ORG3	2	75.02
IPM4/ORG4	2	0.71
IPM5/ORG5	1	84.87
IPM6/ORG6	1	7.54
IPM7/ORG7	1	49.97

<u>Table 15:</u> The difference in BPC_{tot} between SCENorg and SCENipm

However, assessing the total loss of BPC_{tot} requires taking into account the changes in Pp abundance, as well as the changes in BPC_{tot}. For SCENorg, the absolute loss of biological pest control due to the reduction in natural predators species richness has been calculated as the sum of decrease in predation (Ppe and Ppn consumed) and the increase in Ppn and Ppa. With a reduction in the number of predators from 3 to 2, the potential loss in BPC increases substantially with a factor between 10 to 84 times as compared to the BPC provided by 3 predators. An additional loss of a predator species decreases the BPC with a factor 73 to 171. Equally so, the absolute BPC_{tot} relative to the absolute pest insect numbers, reduces from 10.72% for the presence of three predators, to between 4.45% and 1.08% for 2 predators, and decreases further to between 0.71% and 0.02% for the presence of only one predator.

SCENorg	**Pred.**	**$Pp_{en(x)}$ x 10^6**	**BPC_{tot} x 10^6**	**Pp_I x 10^6**	**C_{loss} x10^6**	**BPC_{loss} x10^6**	**$BPC_{rel.\ loss}$**	**$BPC_{tot}/Pp_{en(x)}$**
ORG1	3	1237.11	132.59					10.72
ORG2	2	2550.87	113.43	1313.77	19.16	1332.92	10.05	4.45
ORG3	2	8130.10	87.89	6893.00	44.70	6937.69	52.32	1.08
ORG4	2	12632.92	290.05	11395.81	-157.46	11238.36	84.76	2.30
ORG5	1	10905.15	77.66	9668.04	54.93	9722.97	73.33	0.71
ORG6	1	16005.04	27.04	14767.93	105.55	14873.48	112.18	0.17
ORG7	1	23888.50	4.00	22651.39	128.59	22779.98	171.81	0.02

Table 16: Absolute and relative losses for biological pest control of SCENorg as compared to SCENorg1.

Alternatively, for SCENipm, the potential loss in BPC increases with a factor 19 to 99 as compared to the BPC provided by three predators and with a factor 84 to 125 for the additional loss of a predator γthe presence of three predators, to between 10.38% and 0.13% for 2 predators, and decreases further to between 8.33% and 0.11% for the presence of only one predator.

SCENipm	**Pred.**	**$Pp_{en(x)}$ x 10^6**	**BPC_{tot} x 10^6**	**Pp_I x 10^6**	**$Pp_{insecticides}$** x10^6	**C_{loss} x10^6**	**BPC_{loss} x10^6**	**$BPC_{rel.\ loss}$**	**$BPC_{tot}/Pp_{en(x)}$**
IPM1	3	671.39	69.74						10.39
IPM2	2	671.37	69.72	-0.02	4412.31	0.03	4412.33	63.26	10.38
IPM3	2	790.86	65.94	119.47	1384.39	3.81	1388.20	19.90	8.34
IPM4	2	1622.69	2.05	951.30	6856.04	67.70	6923.74	99.27	0.13
IPM5	1	790.85	65.91	119.45	5918.36	3.83	5922.19	84.91	8.33
IPM6	1	746.33	2.04	74.94	12964.58	67.71	13032.28	186.86	0.27
IPM7	1	1871.74	2.00	1200.34	8686.13	67.74	8753.87	125.51	0.11

Table 17: Absolute and relative losses for biological pest control of SCENipm as compared to SCENipm1.

3.3 Correlation between pest insect density and crop damage

For each scenario, the maximum pest density δ_{ppa} ($ha^{-1}y^{-1}$) and the correlation between δ_{ppa} and the percentage of black pears γ for the four hypothesized relationships γ_{lin}, γ_S, γ_{log}, γ_{exp} was obtained (see ANNEX A.) On the one hand, the low impact function assumes a profit maximization principle and therefore, the economic threshold level is set at 1% black pears. Due to the linear character of γ_{lin}, the potential maximum for γ equals 11.28%. On the other hand, the high impact damage function assumes that in reality, the possibility of γ reaching 100% is possible at maximum values of δ_{ppa}.

The results reveal that all SCENipm remain under the economic threshold level (ETL) whilst the majority of SCENorg are above the ETL. The only exceptions are ORG_1 which is the most plausible since it is the model with the highest species richness for natural predators and ORG_2. It is questionable whether ORG2 in fact is significantly different from the ETL and this reveals the importance of the presence of multiple predators to avoid economic damage to occur.

The low impact damage scenario shows damage levels between 0.01% and 1.72% (resp.0.01 %and 11.28%) for SCENipm (resp. SCENorg). The high impact damage scenario reveals damage levels between 0.65% and 24.69% (resp. 1.46% and 99.89%) for SCENipm (resp. SCENorg).

3.4 Economic impact of a reduction in species diversity on gross income

Selling prices for 1st class, 2nd class and organic pears were obtained for the period 2009-2013. The average selling price for all years for non-organic pears was 0.57 €kg^{-1} with $\mu_1 = 0.70$, μ_2= 0.39, μ_3= 0.88 with s_1= 0.15, s_2= 0.12, s_3= 0.17 n_1=20, n_2=15, n_2=15 resulting in a 95% confidence interval for 1st class pears (resp. 2nd class pears; organic pears) of [0.63;0.78] (resp.[0.32;0.46];[0.78;0.97]). The gross income for SCENorg for the low impact damage function (resp. high impact damage function) ranged between 29282 €ha^{-1} and 30577 €ha^{-1} (resp.20101 €ha^{-1} and 29678 €ha^{-1}) and between 24427 €ha^{-1} and 24463 €ha^{-1} (resp.23125 €ha^{-1} and 24013 €ha^{-1}) for SCENipm. The low impact scenario reveals losses between 0.26% and 2.10% (resp. 0.001% and 0.1%) for SCENorg (resp. SCENipm) for the loss of one natural predator, and between 1.69% and 4.23% (0.002% and 2.15%) for SCENorg (resp. SCENipm) for the loss of two predators. For the high impact scenario, the reduction in gross income ranges between 4.23% and 18.67% (resp. 0.001% and 3.06%) for SCENorg (resp. SCENipm) the loss of one natural predator, and between 17.13% and 32.27% (resp. 0.41% and

3.70%) for SCENorg (resp. SCENipm) for the loss of 2 natural predators. The low impact scenario reveals that the value of a decrease in species richness for SCENorg (resp. SCENipm) ranges from 79 to 641 €ha^{-1} (resp. 1 to 25 €ha^{-1}) for a loss of one predators and from 517 to 1295 €ha^{-1} (resp. 1 to 36 €ha^{-1}) for the loss of 2 predators, whilst the high impact scenario reveals that the value of a decrease in species richness for SCENorg (resp. SCENipm) ranges from 1256 to 5540 €ha^{-1} (1 to 734 €ha^{-1}) for a loss of one predator and from 5084 to 9576 €ha^{-1} (98 to 888 €ha^{-1}) for the loss of two predators .

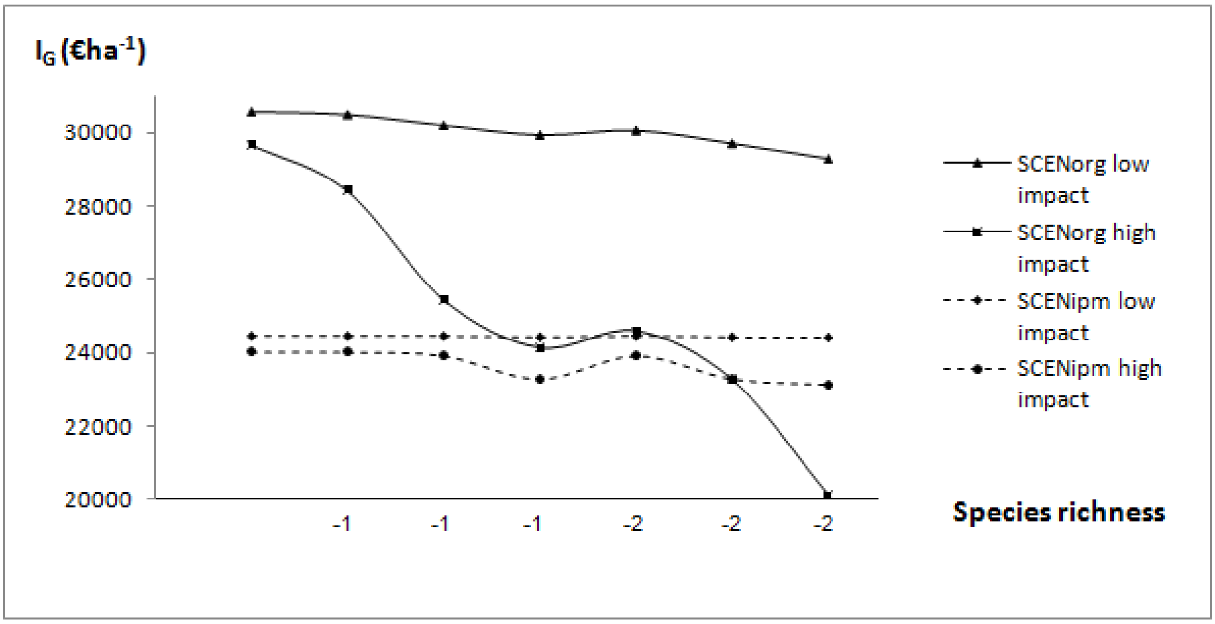


Figure 18: The effect of a loss of species diversity on the gross income (€ha^{-1})

The value of the loss in species abundance is represented by the average difference in gross income between SCENorg and SCENipm and ranges between 19.55% reduction in gross income (IPM_1/ORG_1) or 5889 €ha^{-1} to 3.71% (IPM_7/ORG_7) or 915 €ha^{-1} .

The intermediary results might seem to indicate a higher dependency for organic farming on the presence of natural predators with the possibility of a significantly higher gross income, provided that enough natural predators remain in the agroecosystem. Gross income for SCENipm is on average significantly lower than for SCENorg for all levels of species diversity but is less vulnerable to changes in species diversity. The decrease in variability results from the decrease in the presence of *Pear psylla* and hence a lower percentage of black pears. However, it should be noted here that field measurements produced counterintuitive measurements, and that IPM fields did not show lower pest insect densities, but densities that were considerably larger than organic plots. Therefore, iIt should be noted that based on the gross income, it cannot be concluded that the use of insecticides reduces risk in pear production, as is shown later on in more detail (see discussion 4.3). Furthermore, it is expected that the inclusion of external costs in the framework could significantly affect the results for IPM.

3.5 Economic impact of a reduction in species diversity on farm income

When assessing the effects of a decrease in species diversity on income, not only the difference in gross income (yield and prices) is taken into account but also the differences in cost structure with regards to inputs used. Descriptive statistics show that: 1) the amount of non-consumable pears sold as feed is on average 20% less for organic production, due to lower yields in total (μ_{ipm}=458.25 kgha^{-1}, μ_{org}= 366.60 kgha^{-1}), 2) organic farmers can on average claim 52% higher subsidies (μ_{ipm}= 138.61 €ha^{-1}, μ_{org}= 210 €ha^{-1}), 3) Crop protection for IPM accounts for 1650 €ha^{-1}, for organic production, no costs have been taken into account and 4) organic management requires 30% more labor (μ_{ipm}= 4270.70 €ha^{-1}, μ_{org}= 5789.17 €ha^{-1}). For reasons of simplicity, other production factors (e.g. conservation costs, maintenance, packaging) are assumed equal for both scenarios.

The first results of a decrease in species abundance on farm income are of comparable magnitude to the gross income decreases. A comparison between SCENorg and SCENipm yields on average 14498.81 €ha^{-1} for Org$_1$ and 12525.27 €ha^{-1} for IPM1, resulting in a loss of 1973.54 €ha^{-1}.

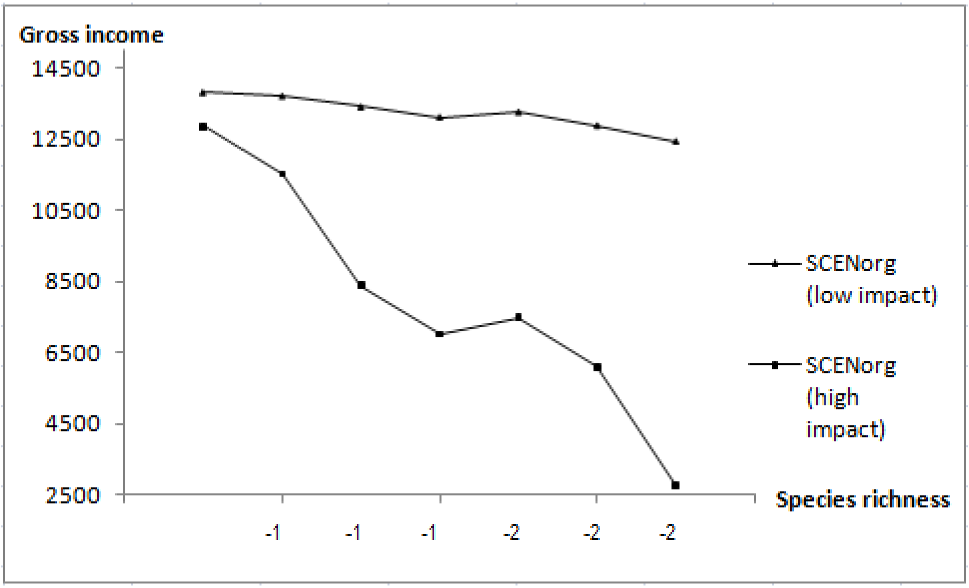


Figure 19: The effect of a loss of species diversity on the farm income for organic management (€ha^{-1})

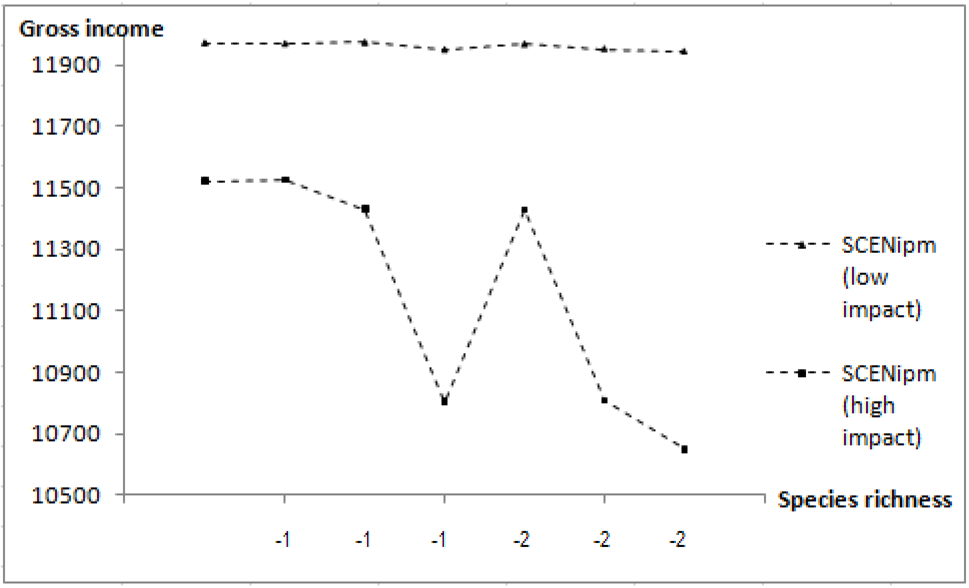


Figure 20: The effect of a loss of species diversity on the farm income for IPM (€ha^{-1})

3.6 Summary of the results

3.6.1 Monetary valuation of losses in species abundance

Species abundance losses for SCENipm1 for An (resp. Af, Hp) accounted for 45.31% (resp. 37.18%; 20.44%) as compared to SCENorg1. Consequently, gross income losses accounted for 19.09% and farm income losses accounted for 10.38%. In absolute terms, the loss of biological pest control due to the loss of species abundance accounts for economic losses between 1334.21 €ha^{-1} and 5664.99 €ha^{-1}. This is the value which is potentially lost with the loss of species abundance and can therefore be assumed an objective value of increased species abundance.

3.6.2 Monetary valuation of losses in species richness

The effect of the loss of entire species on the provisioning of biological pest control and consequently on the decrease of yield quality cannot be neglected. For SCENorg the loss of one species resulted in a decrease of BPC with a factor 10.05 to 87.76, and for the loss of two species, BPC decreased between 73.33 and 178.81 times. As a consequence, the amount of black pears encountered and therefore the gross income (resp. farm income) decreases between 4.23% and 18.67% (resp. 9.22% and 73.59%) for the loss of one species, and between 17.13% and 32.27% (resp.26,47% and 96.36%) for the loss of two species. In absolute terms, the effects of the loss on farm income and gross income are relatively similar. Therefore, irrespective of gross or farm income, the values which can be assigned to the ecological functions performed by natural predators range between 778 €ha^{-1} and 5832 €ha^{-1} (one predator) and 4671 €ha^{-1} and 12284 €ha^{-1} (two predators) (see figure 21).

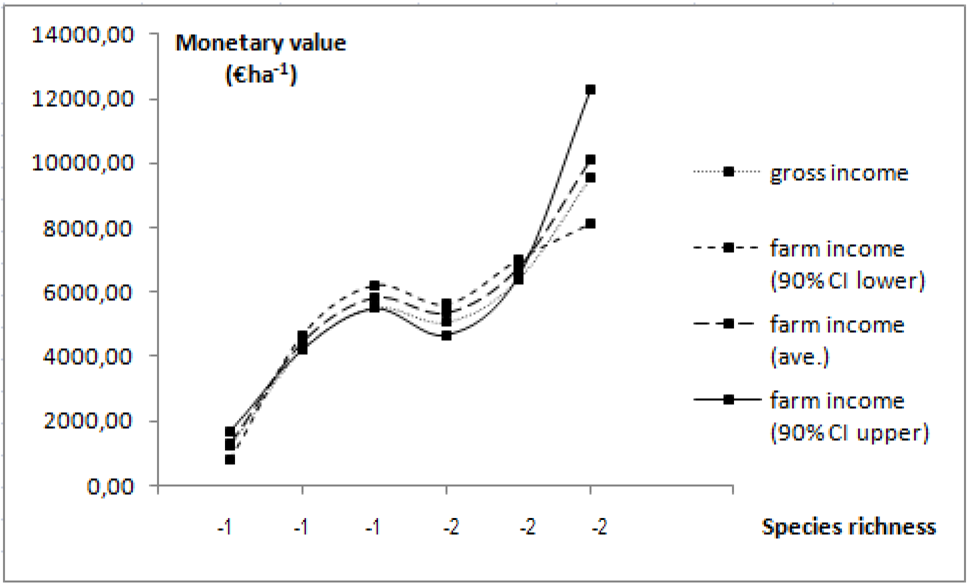


Figure 21: Monetary value of species richness in organic management based on gross and farm income losses

Results for IPM have been represented in figure 22 and represent value ranges between 0 €ha^{-1} and 733.88 €ha^{-1} (one predator) and 93.42 €ha^{-1} and 888.27 €ha^{-1} (two predators) (see figure 22).

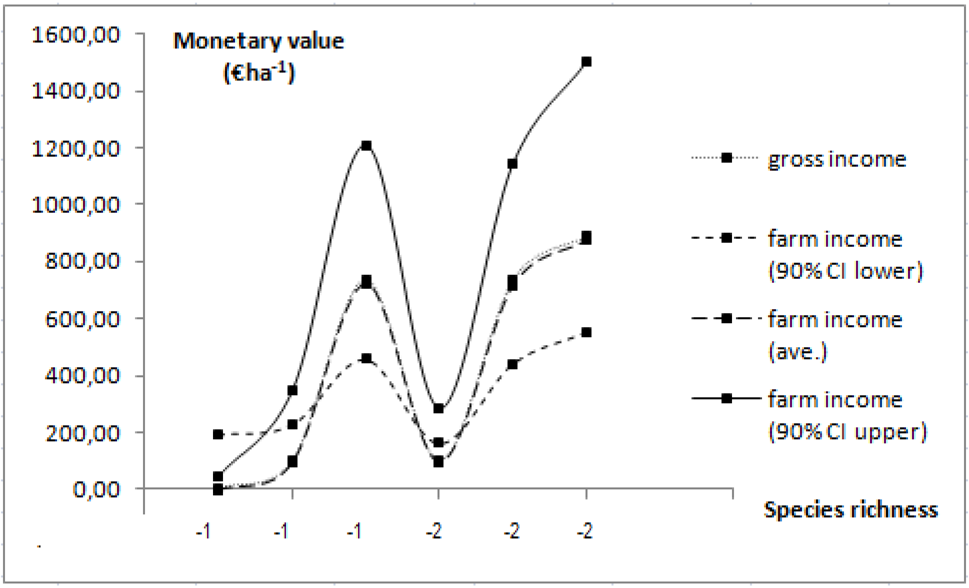


Figure 22: Monetary value of species richness in IPM based on gross and farm income losses

It should be noted that the results for SCENipm are expected to be much higher and at the moment do not represent actual field conditions (see discussion 4.3).

4. Discussion

The results as presented in this analysis are assumed to be a conservative estimate of an objective indirect use value and interpretation of the results needs to be viewed within a wider framework of (1) functional redundancy, (2) uncertainty of economic damage threshold quantities, (3) impact of fertilizer and pesticide use on pear psylla population dynamics, (4) effect of omitted pesticide applications, (5) employment of conservative model parameters, (6) external costs of pesticide use, (7) potential additional benefits of increased species diversity on higher trophic levels and (8) post-harvest treatments to reduce blackness of pear skin.

4.1 The effect of functional redundancy on marginal values

The indirect use value for the presence of natural predators that is inferred here by examining the impact of the functional role of the species in the ecosystem on the reduction in private and external costs highly depends on the functional redundancy of these species. The concept of functional redundancy is based on the principle that some species perform similar roles in ecosystems and may therefore be substitutable with little impact on ecosystem processes (Lawton and Brown, 1993). Therefore the effect of species loss depends on (i) the range of function and diversity of species within a functional group, (ii) the relative partitioning of variance in in functional space between and within functional groups, and (iii) the potential for functional compensation of the species (Rosenfeld, 2002). Whilst *Anthocoris nemoralis*, *Allothrombidium fuliginosum* and *Heterotoma planicornis* are all natural predators of *Cacopsylla pyri,* it could be assumed that they are functionally redundant and that the impact of the loss of one natural predator does not significantly alter the impact on biological pest control. It is argued here that although providing the same function they are not functionally redundant due to (i) exertion of ecological function occurs on different time scales: species that occur on critical timings e.g. when high pest density levels are expected, can be considered of a higher functional importance, (ii) differences in duration of ecological function, (iii) differences in degree of specialization: whilst some species thrive in a wide variety of environmental conditions, some require specific conditions for survival and rendering them less resilient to external shocks, and (iv) differing impacts on other species in the ecosystem due to predation preferences: generalists versus specialists.

The relationship between functional redundancy and economic value of species can be represented as an exponential decline whereby the marginal value of the loss of the first species is small and the loss of the loss of the last species is infinite. While in this analysis only three species have been modeled, the effect of the interaction with other species has been included in the model. Therefore, the economic values represented in this analysis do not reflect values on either of the extreme ends of the marginal value curve.

It is argued here that although species perform the same function, they are not functionally redundant, that the loss of one species can significantly alter the provisioning of ecological functions and that attributing an indirect use value to the loss of one species is justified. Furthermore, our simulation model does effectively take into account differences in timing, duration and prey preference. The indirect use value therefore reflects the functional differences and effectively takes into account the importance of the different species for the biological pest control of *Cacopsylla pyri*.

4.2 Economic threshold level (ETL) for pest insect density

In our analysis, two damage functions (low and high impact damage function) are employed to relate the effect of differences in pest insect density with economic damage levels by quantifying percentages of black pears. Pest insect densities larger than 1000 adults per 10 beatings, yielding ‘detectable damage’ was translated as 1% of black pears under the assumption that famers maximize profits. However, this also fixed the absolute maximum amount of black pears at 11.25%. Expert opinion affirmed however that yields consisting of 100% black pears are a real possibility (under the assumption that no control measures are taken to prevent the pest insect from reaching maximum density levels. This would fix the economic threshold level for detectable damage at between 1.32 and 32.02 % of black pears. This substantiates the evidence for the high impact damage function to better reflect reality conditions and by consequence, the higher economic value appears to better represent the importance of the presence of natural predators.

4.3 Impact of fertilizer and pesticide use on pest insect density

Comparison of field data from all years and both datasets consistently show pear psylla population numbers for IPM to be significantly higher than in organic fields with up to tenfold increases and more for IPM as compared to organic. The rationale behind the use of insecticides in effectively decreasing pest insect densities can therefore be questioned. It is the belief of the authors and fruit sector consultants in the field that several reasons may be at the cause of this counterintuitive observation: (i) the use of fertilizers increases the attractiveness of leaves for pear psylla adults due to their 'healthier and greener' appearance. The mobility of adults would allow inflow from adjacent plots, thereby increasing pest insect density, (ii) the effect of pesticide spraying results in 'shinier' leaves, thereby also increasing leaf attractiveness and causing adult inflow and (iii) the reduced presence of natural predators decreases predation and allows for higher pest insect densities. In this analysis however, the starting point is SCENorg from which SCENipm is modeled based on pest insect death rates of 95%, resulting in lower pest insect densities for SCENipm. Potential inflows from adults and consequent damage has therefore not been modeled, which severely underestimates the importance and values of natural predators for IPM management.

4.4 Effect of omitted pesticide use

In the ecological model, the effect of 7 insecticides with active ingredients against pear psylla propagation have been included . In reality, over 110 different herbicides, insecticides, fungicides and other active ingredients (e.g. growth regulators) are applied throughout the year (ANNEX C). The potential for additional serious harmful effects on natural predators therefore seems plausible and has not been included in the model. Hence, the death rates of natural predators as modeled in this analysis are expected to be a severe underestimate, speaking in favor of higher values for the presence of natural predators.

4.5 Employment of conservative model parameters

Two model parameters, (i) death fractions of natural predators and (ii) biological duration of action of insecticides have been modeled with values at the low end of the spectrum. Death fractions of natural predators are specified as ranging between <25%, 25-50%, 50-75% and >75% and for uptake in the model, values on the low end of the spectrum have been incorporated, therefore underestimating the loss in species abundance.

4.6 External costs of pesticide use

The presence of natural enemies reduces the number of pest insects, and therefore also reduces the amount of insecticides which needs to be applied. Hence, the presence of natural predators indirectly reduces the external costs associated with the use of pesticides. A large number of surveys have been published, revealing the external costs to society of pesticide application (Pimentel et al., 1993), eg. the effects of pesticide application on public health, groundwater contamination, and fishery losses. The external costs of pesticide use have not (yet) been modeled and would significantly alter results in such a way that the value of natural predators for SCENipm would increase due to their contribution to decreasing external costs.

4.7 Potential beneficial effects of increased species diversity

The effect of increased species diversity and/or increased species abundance on higher trophic levels has not been taken into account but it is expected that potential benefits exist, thereby further increasing the importance and values of the species under analysis.

4.8 Post-harvest treatments

Post-harvest treatments (e.g. a washing step) can be employed in order to reduce visible blackening of the skin, and hereby possibly increasing market values of production. Nevertheless, market values do not only depend on blackening of pear skin but also depends on e.g skin coarseness and pear size. Economic costs of such a washing step could be taken into account but this does not guarantee an increase in sale price.

5. Conclusion

Acknowledgments

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ANNEX A

	SCENipm			SCENorg		
	Min	Av.	Max	Min	Av.	Max
	Benefits					
Total yield (kgha^{-1})	**29838.06**	**34800.00**	**39802.94**	**23870.45**	**27850.00**	**31842.35**
Fruit for consumption (kgha^{-1})	**29548.31**	**34360.00**	**39176.19**	**23638.65**	**27500.00**	**31340.95**
Selling price (€kg^{-1})	**0.63**	**0.70**	**0.78**	**0.78**	**0.88**	**0.97**
Fruit not for consumption (kgha^{-1})	**136.46**	**460.00**	**780.04**	**109.17**	**370.00**	**624.03**
Selling price (€kg^{-1})	0.03	0.07	0.11	0.03	0.07	0.11
	Economic analysis (ha^{-1})					
Gross benefits						
Main products (€ha^{-1})	18692.89	20150.00	26079.68	16126.53	20150.00	26079.68
Subsidies (€ha^{-1})	**79.82**	**140.00**	**170.01**	**125.70**	**210.00**	**294.30**
Other products (€ha^{-1})	40.19	130.00	183.99	40.19	130.00	183.99
Plantation growth (€ha^{-1})	343.81	490.00	609.32	343.81	490.00	609.32
Variable costs total	8836.16	9500.00	10077.68	8836.16	9500.00	10077.68
Sowing material (€ha^{-1})	3.68	15.00	51.35	3.68	15.00	51.35
Fertilizers (€ha^{-1})	**227.31**	**280.00**	**327.29**	**227.31**	**280.00**	**327.29**
Crop protection (€ha^{-1})	**1414.13**	**1650.00**	**1998.16**	**0.00**	**0.00**	**0.00**
Seasonal wages and labour (€ha^{-1})	3816.13	4200.00	4453.21	4933.41	5400.00	6006.62
Maintenance (€ha^{-1})	1152.52	1200.00	1255.15	1152.52	1200.00	1255.15
Packaging (€ha^{-1})	166.94	350.00	530.44	166.94	350.00	530.44
Preservation (€ha^{-1})	373.47	600.00	687.80	373.47	600.00	687.80
Other delivery costs (€ha^{-1})	558.20	680.00	877.03	558.20	680.00	877.03
Other variable costs (€ha^{-1})	486.04	530.00	579.56	486.04	530.00	579.56
Fixed costs total	4666.09	5200.00	5576.99	4666.09	5200.00	5576.99
Lease/rent (€ha^{-1})	422.22	500.00	529.84	422.22	500.00	529.84
Amortization fixed equipment (€ha^{-1})	992.31	1200.00	1427.12	992.31	1200.00	1427.12
Amortization buildings (€ha^{-1})	643.09	700.00	772.36	643.09	700.00	772.36
Amortization plantations (€ha^{-1})	635.63	650.00	677.42	635.63	650.00	677.42
Interests	1328.76	1520.00	1648.42	1328.76	1520.00	1648.42
General corporate costs	531.14	630.00	668.82	531.14	630.00	668.82

ANNEX B.

		Low impact damage function						High impact damage function					
Model	δ_{Ppa} ($10^6 ha^{-1}$)	γ_{lin} (%)	γ_S (%)	γ_{log} (%)	γ_{exp} (%)	γ_l (%)	γ_u (%)	γ_{lin}	γ_S	γ_{log}	γ_{exp}	γ_l (%)	γ_u (%)
IPM1	91.5455	0.24	0.01	0.58	1.05	0.01	1.05	2.03	0.65	8.75	1.10	0.65	8.75
IPM2	91.5455	0.24	0.01	0.58	1.05	0.01	1.05	2.03	0.65	8.75	1.10	0.65	8.75
IPM3	111.1770	0.29	0.01	0.70	1.06	0.01	1.06	2.47	0.69	10.52	1.12	0.69	10.52
IPM5	111.1784	0.29	0.01	0.70	1.06	0.01	1.06	2.47	0.69	10.52	1.12	0.69	10.52
ORG1	146.9157	0.38	0.01	0.92	1.08	0.01	1.08	3.26	0.77	13.66	1.16	0.77	13.66
IPM4	247.8209	0.64	0.02	1.52	1.14	0.02	1.52	5.51	1.04	21.95	1.28	1.04	21.95
IPM6	247.8257	0.64	0.02	1.52	1.14	0.02	1.52	5.51	1.04	21.95	1.28	1.04	21.95
IPM7	283.5866	0.73	0.02	1.72	1.17	0.02	1.72	6.30	1.16	24.69	1.33	1.16	24.69
ORG2	379.7750	0.98	0.03	2.25	1.23	0.03	2.25	8.44	1.54	31.60	1.46	1.46	31.60
Treshold	386.0000	1.00	0.03	2.28	1.23	0.03	2.28	8.58	1.57	32.02	1.47	1.47	32.02
ORG3	1331.6776	3.45	0.31	6.32	2.07	0.31	6.32	29.59	21.36	73.60	3.79	3.79	73.60
ORG5	1815.2014	4.70	1.01	7.75	2.69	1.01	7.75	40.34	53.68	83.72	6.14	6.14	83.72
ORG4	2134.8315	5.53	2.08	8.53	3.20	2.08	8.53	47.44	75.14	88.17	8.46	8.46	88.17
ORG6	2714.9748	7.03	5.76	9.66	4.39	4.39	9.66	60.33	94.51	93.38	15.10	15.10	94.51
ORG7	4036.5474	10.46	11.28	11.27	9.02	9.02	11.28	89.70	99.89	98.23	56.63	56.63	99.89

Table B1: Lower and upper values for the percentage of black pears for changing pest density levels.(* ETL = Economic Treshold Level). Top: the low impact damage function assumes the ETL is reached at 1% black pears. Bottom: the high impact damage model assumes 100% black pears at maximum pest density levels.

ANNEX C.

1	2,4-D	a_herb
2	2-(1-Naphthyl)Acetamide	d_abes
3	6-Benzyladenine	d_abes
4	Abamectine	b_insec
5	Alfa-Naftylazijnzuur	d_abes
6	Amitrol	a_herb
7	Ammoniumglufosinaat	a_herb
8	Ammoniumthiocyanaat	a_herb
9	Azocyclotin	b_insec
10	Bitertanol	c_fung
11	Captan	c_fung
12	Chloorpyrifos	b_insec
13	Chloortoluron	a_herb
14	Clofentezin	b_insec
15	Clopyralid	a_herb
16	Cyprodinil	c_fung
17	Delta-Aminovaleriaanzuurbetaine	d_abes
18	Deltamethrin	b_insec
19	Dichlobenil	a_herb
20	Dichloorprop-P	a_herb
21	Diethofencarb	c_fung
22	Difenoconazool	c_fung
23	Difethialon	d_abes
24	Diflufenican	a_herb
25	Dimethoaat	b_insec
26	Dimethomorf	c_fung
27	Diquat	a_herb
28	Dithianon	c_fung
29	Dodine	c_fung
30	Ethefon	d_abes
31	Fenbutatin-Oxide	b_insec
32	Fenhexamid	c_fung
33	Fenmedifam	a_herb
34	Fenoxycarb	b_insec
41	Fluroxypyr	a_herb
42	Fosethyl	c_fung
43	Gamma-Aminoboterzuurbetaine	d_abes
44	Geesterde Koolzaadolie	d_abes
45	Gibberellinezuur A3	d_abes
46	Gibberellinezuur A4+7	d_abes
47	Glycinebetaine	d_abes
48	Glyfosaat	a_herb
49	Hexythiazox	b_insec
50	Imazalil	c_fung
51	Imidacloprid	b_insec
52	Iprodione	c_fung
53	Isodecyl-Alcohol Ethoxylaat	d_abes
54	Koperhydroxide (Uitgedrukt In Cu)	c_fung
55	Koperoxychloride (Uitgedrukt In Cu)	c_fung
56	Kresoxim-Methyl	c_fung
57	Lambda-Cyhalothrin	b_insec
58	Linuron	a_herb
59	Mancozeb	c_fung
60	Maneb	c_fung
61	Mcpa	a_herb
62	Mecoprop-P	a_herb
63	Mepanipyrim	c_fung
64	Metamitron	a_herb
65	Metazachloor	a_herb
66	Metconazool (Cis/Trans 84/16)	c_fung
67	Methiocarb (Sl)	d_abes
68	Metiram	c_fung
69	Minerale Paraffine-Olie	d_abes
70	Myclobutanil	c_fung
71	Paraffine Olie	d_abes
72	Paraffineolie (Hoge Sulfoneringsindex)	b_insec
73	Paraquat	a_herb
74	Parathion	b_insec
81	Penconazool	c_fung
82	Pendimethalin	a_herb
83	Pirimicarb	b_insec
84	Tebufenpyrad	b_insec
85	Thiofanaat-Methyl	c_fung
86	Thiram	c_fung
87	Triadimenol	c_fung
88	Triclopyr	a_herb
89	Boscalid	c_fung
90	Trimesium-Glyfosaat	a_herb
91	Zwavel	c_fung
92	Kaoline	d_abes
93	Schuimremmer	d_abes
94	Siliconen	d_abes
95	Cyflufenamide	c_fung
96	Spirodiclofen	b_insec
97	1-methylcyclopropeen	d_abes
98	Flonicamid	b_insec
99	Methoxyfenozide	b_insec
100	SPIROTETRAMAT	b_insec
101	Chloorantranilipole	b_insec
102	Etoxazool	b_insec
103	Kwartzand	d_abes
104	Kaliumwaterstofcarbonaat	a_herb
105	Acetamiprid	b_insec
106	Pyraclostrobin	c_fung
107	Fenamidone	c_fung
108	Gibberelline A4+7	d_abes
109	Indoxacarb	b_insec
110	Prohexadion	d_abes
111	Tepraloxydim	a_herb
112	Thiacloprid	b_insec
113	Thiamethoxam	b_insec
114	Trifloxystrobine	c_fung

35	Fenpyroximaat	b_insec
36	Flocoumafen	d_abes
37	Fluazifop-P-Butyl	a_herb
38	Fludioxonil	c_fung
39	Flufenoxuron	b_insec
40	Fluquinconazool	c_fung
75	Pyridaben	b_insec
76	Pyrimethanil	c_fung
77	Quinoxyfen	c_fung
78	Spinosad	b_insec
79	Tebuconazool	c_fung
80	Tebufenozide	b_insec
115	Aminopyralide	a_herb
116	Laminarine	d_abes

Table C1: lists of known pesticides used in 2012 with a_herb = herbicides, b_insec = insecticides, c_fung = fungicides, d_abes = other active ingredients.