

1 **Monetary valuation of natural predators for biological pest control in pear production**

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11 **Abstract**

12 In spite of global actions, biodiversity is declining at an alarming rate. Despite the need for  
13 objectively comparable monetary standards to include biodiversity arguments in  
14 policymaking, research on the relationship between species diversity and its valuation from a  
15 societal perspective is still scarce.

16 In this paper, a methodological framework for the valuation of natural predators based on  
17 their ecological role in the agroecosystem is introduced. The framework integrates a dynamic  
18 ecological model simulating interactions between species with an economic model, thereby  
19 quantifying the effect of reduced numbers of **natural predators on the net farm income**. The  
20 model attributes an objective monetary value to increased species diversity through the  
21 changes in the provisioning of a marketable good.

22 Results indicate that the loss of three predators could decrease net farm income with 88.86  
23 €ha<sup>-1</sup> to 2186.5 €ha<sup>-1</sup>. For the pear production sector in Flanders in 2011, this constitutes to an  
24 indirect use value of 0,68 million € for one predator and 16.63 million € for the presence of  
25 three predators. The aim is to provide a justification for the argument for biodiversity  
26 conservation, based on the ecological function of species, through the delivery of comparable  
27 monetary standards.

28 Keywords: monetary valuation, ecological function, biodiversity loss, biological pest control,  
29 ecological-economic modeling

## 30 **1. Introduction**

31 In spite of global actions, biodiversity is declining at an alarming rate (Butchart et al., 2010).  
32 The transformation of natural landscapes to agricultural systems, the abandonment of  
33 farmland with high natural values, and the intensification and changing scale of agricultural  
34 operations are the key processes driving low ecosystem quality and biodiversity losses in  
35 agro-ecosystems (Liu et al., 2013; Reidsma et al., 2006; Smith et al., 2013). Available  
36 evidence strongly indicates the importance of agro-ecosystem restoration for environmental  
37 benefits and acknowledges the potential to simultaneously minimize biodiversity harm at the  
38 local level and increase farm yields (Barral et al., 2015; Cunningham et al., 2013).

39  
40 Although measurements of biodiversity have often been investigated, analyses at the farm  
41 scale and specific studies providing insights into factors driving agro-ecosystem community  
42 structure are scarce (Birrer et al., 2014; Farnsworth et al., 2015; Turtureanu et al., 2014).  
43 Furthermore, habitat and increased numbers of natural predators facilitate the provisioning of  
44 important ecosystem services such as maintaining agricultural pest control, and may increase  
45 efficiency in controlling pests. However, the relationship between natural predators and pest  
46 reduction potential is not well established (Chaplin-Kramer et al., 2013; Letourneau et al.,  
47 2015). More specifically, the control of pests and diseases by biological control agents  
48 contributes positively to the provisioning of agricultural products of a better quality or in  
49 higher quantities, however the relationship between the presence of natural predators and pear  
50 production in particular has not been investigated yet. Mathematical models for biological  
51 pest control have proposed the use of linear feedback control strategies to indicate how  
52 natural enemies should be introduced into the environment (Rafikov and de Holanda Limeira,  
53 2011).

54

55 Farmers are in need of supporting evidence of biodiversity benefits outweighing the  
56 opportunity costs incurred in order to strengthen the argument for biodiversity conservation at  
57 the farm level. Moreover, without economic valuation of the environment, policy decisions  
58 that contradict economic rationality could be supported. In spite of the need for objectively  
59 comparable monetary standards, empirical literature investigating the relationship between  
60 species diversity and its valuation from a farmer's perspective is still scarce (Finger and  
61 Buchmann, 2015). The elicitation of values for biodiversity with the aid of stated preference  
62 methods suffers from the generally low level of awareness and understanding of what  
63 biodiversity means on the part of the general public (Bräuer, 2003; Christie et al., 2006).  
64 Furthermore, the willingness-to-pay (WTP) for species that are unfamiliar or undesired by the  
65 general public could yield extremely low values despite the fact that these species could be  
66 performing indispensable ecological services and thereby contribute indirectly to the farmers'  
67 income. This, combined with the complexity of biodiversity (Feest et al., 2010), might just  
68 overstretch the capacity of the usual stated preference valuation techniques for the valuation  
69 of biodiversity (Bartkowski et al., 2015). Revealed preference techniques have the advantage  
70 that they rely on the observation of peoples' actions in markets. However, the majority of  
71 species do not have a market price. Letourneau et al. (2015) value the changes in natural  
72 enemy diversity by studying changes in producer and consumer surplus. They estimate that  
73 losses in natural enemy species richness in squash and cucumber fields in Georgia and South  
74 Carolina could cost society between \$1.5 and \$12 million in social surplus every year.

75

76 In this paper we provide a complementary approach and overcome some of the limitations  
77 mentioned by Letourneau et al. (2015) by (i) including an ecological model that allows for  
78 spatial and temporal variation in the ecosystem service potential of natural enemies, their

79 interactions with pests and the effect of those interactions on pest control cost savings, (ii)  
80 providing an alternative approach when the relationship between natural enemies and crop  
81 damage is not known, as is true for the majority of cases, (iii) confirming the results of  
82 Letourneau et al. (2015) that values are case specific and providing these values for a different  
83 crop in a different climatic zone, with a different pest insect and natural enemies and (iv)  
84 including the comparison of realistic alternative scenarios of species richness and measure  
85 economically meaningful data in a field setting that comes close to the conditions that prevail  
86 on actual farms.

87

88 This paper values the biological pest control provided by three natural predators of pear psylla  
89 (*Cacopsylla pyri* L.) (Homoptera: Psyllidae) in organic pear orchards in Flanders (Belgium).

90 Three main research hypotheses are investigated:

91  $H_1$ : a decrease in natural predators' species richness causes a decrease in pest suppression

92  $H_2$ : a reduction in species richness of natural predators reduces marketable agricultural  
93 production, thereby decreasing farm revenues

94  $H_3$ : an alternative valuation method for natural predators based on their ecological function in  
95 the ecosystem can be identified

96 The first hypothesis is quantified through the development of an ecological simulation model;  
97 the second hypothesis is supported by the use of production functions and a direct market  
98 valuation technique and the third hypothesis integrates all three research tools: an ecological  
99 simulation model with a production function approach and a direct market valuation  
100 technique.

101 The approach results in a monetary value for marginal changes of biodiversity losses (here:  
102 reduced number of natural predators) whereby the functional role of the species in the  
103 ecosystem (here: pest control) is the key mechanism for affecting the provisioning of a

104 marketable good (here: agricultural production). The aim is to provide support for the  
105 decision making process so that not only the costs of biodiversity conservation can be taken  
106 into account but also the monetary benefits.

## 107 **2. Case study description: biological pest control of pear psylla**

108 Apple and pear production in Flanders accounted for 13764 hectares in 2011 and increased to  
109 14285 ha in 2013, comprising 3% of all farmland. Since 2005, pear production comprised **just**  
110 **over half the hectarage** with 7607 ha in 2011 and 7995 ha in 2013. The province of Limburg  
111 accounts for 85% of the total apple and pear production in Flanders. In 2011, an average farm  
112 possessed 12,0 hectares **of pear plantations** and 14,4 hectares in 2013. Organic production  
113 accounts for only a small fraction but **production** areas increased **by** 224% over the period  
114 2002 – 2012 from 25,09 ha to 58,07 ha. Average yields **were** 36031 kg per ha in 2011 and  
115 38681 kg per ha in 2013, with a maximum of 44751 kg per ha in 2014 (Van der Straeten,  
116 2016). Yearly sales volumes of pears amounted to almost 340 million kg in 2014 (NIS, 2015).  
117 Annual sales revenues ranged between 15133 €ha<sup>-1</sup> in 2011 and 20114 €ha<sup>-1</sup> in 2013 (Van der  
118 Straeten, 2016). Yearly average selling prices for the period 2009-2013 were 0.57 €kg<sup>-1</sup> for  
119 first-class pears, 0.39 €kg<sup>-1</sup> for second-class pears and 0.88 €kg<sup>-1</sup> for organic pears (personal  
120 communication Regional Auction Borgloon). Assuming that annual sales volumes would  
121 consist of second class pears only, 55.68% of gross revenues would be lost since if harvests  
122 consisted of **only** second class pears **and** gross revenues would amount to 11736 €ha<sup>-1</sup> as  
123 compared to 26481 €ha<sup>-1</sup> for harvests consisting of only first class pears (Van der Straeten,  
124 2016). The sector is characterized by a decrease in the number of farms and an increase in the  
125 average **size**. Sales volumes and revenues remain extremely volatile due to changing  
126 environmental and market conditions (Platteau et al., 2014).

127 A major threat for the pear production industry is pear psylla (*Cacopsylla pyri*). The adults  
128 cause damage both directly by extracting nutrients from the meristem tissue, and indirectly by

129 causing russet and roughness on pear skin. Pear psylla's status as a major pest is based on its  
130 damage potential and its ability to develop resistance to insecticides. Through the production  
131 of honeydew, the growth of black, sooty fungi, causing so-called “black pears” is facilitated.  
132 It russets the pear skin and causes the fruit to be downgraded, thereby decreasing its market  
133 value (Erler, 2004). Literature quantifying the relationship between pest insect density levels  
134 and the occurrence of fruit russet is however scarce (Brouwer, 2008). Research revealed the  
135 failure of conventional chemical control agents against the pear tree psyllid, stressing the need  
136 for alternative strategies such as enhancing natural arthropod enemies (Daugherty et al., 2007;  
137 Erler, 2004; Rieux et al., 1999). Pear psylla are commonly attacked by several different  
138 natural enemies (e.g. *Anthocoris nemoralis* (Heteroptera: Anthocoridae), *Allothrombidium*  
139 *fuliginosum* (Acari: Trombidiidae) and *Heterotoma planicornis* (Hemiptera: Miridae)), of  
140 which *A. nemoralis* is the most common predator. Data collection is comprised of two  
141 independently executed field tests. The first field test comprises field data collected on 7 plots  
142 in organic *Conférence* pear orchards in Hesbaye (Belgium) for two years from 2013 until  
143 2014. Each field test sampled pear psylla eggs and nymphs on multiple days with an interval  
144 of 2-3 weeks (See ANNEX A.1 for data sampling method and pooled results). The second  
145 dataset was obtained from field tests performed every two weeks for the period 2010-2011 on  
146 7 different organic plots in Hageland (Belgium) and Gelderland and Limburg (NL). The same  
147 techniques were used to assess mean egg numbers and larvae numbers (visual scouting and  
148 the beating tray method) (see ANNEX A.3).

149 Counts for the presence of beneficial insects were performed between February and October  
150 of 2013 and 2014 in organic *conférence* pear orchards (see ANNEX A.2 for data sampling  
151 methods and pooled counts).

### 152 **3. Methodology**

#### 153 **3.1 Ecological model construction**

154 The ecological model simulates predator-prey dynamics between the pest insect and three of  
155 its main natural enemies to analyze the effect on pear psylla (Pp) abundance in case of a  
156 reduction in species diversity and abundance of natural predators. The main criterion for  
157 selection of the natural enemies is the importance of a species as main pear psylla antagonist  
158 and has been verified through expert opinion and literature review. With the use of STELLA  
159 10.0.6 (Stella; available at <http://www.iseesystems.com>) (Costanza and Gottlieb, 1998;  
160 Costanza and Voinov, 2001), the biodemographics of a pest insect *Cacopsylla pyri* (Pp) and  
161 the interaction with (i) *Anthocoris nemoralis* (An), (ii) *Allothrombidium fuliginosum* (Af) and  
162 (iii) *Heterotoma planicornis* (Hp) (Erlor, 2004) are simulated over a period of one year  
163 whereby:

$$164 \quad \frac{dn_{Pp}}{dt} = f(n_{An}, n_{Af}, n_{Hp}, n_{other}) \quad (\text{eq. 1})$$

165 with  $n$  the species abundance and  $n_{other}$  the effects of other predators not explicitly included  
166 in the model.

167 Initial model parameter values are allowed to vary on a daily basis and can be found in  
168 ANNEX B. The food fractions (the fraction that Pp makes up in a daily diet of a natural  
169 predator) were set at 0.8 for specialists (An) and 0.2 for generalists (Af and Hp) (Piechnik et  
170 al., 2008). The number of Ppe (eggs) and Ppn (nymphs) preyed upon per day are variable and  
171 depend on prey density according to a logistic dependency. The higher the density of Pp, the  
172 more Pp will be subject to predation as opposed to a linear dependency approach. Natural  
173 mortalities for all species are represented as a time-dependent variable longevity. Both  
174 Oviposition and longevity are non-constant parameters, depending on the time of the year and  
175 the adult generation cycle. The carrying capacity for Pp has been determined by excluding  
176 predation under the assumption that resource use did not pose constraints. The growth  
177 function is modeled as a logistic growth curve, followed by a decline of the population.

178 In the model, the effects of omitted species in the agro-ecosystem have been taken into  
179 account in various ways:

180 (i) An, Af and Hp are themselves subjected to predation from omitted species at  
181 higher trophic levels and this effect has been taken into account by the inclusion of  
182 a predation fraction for An, Af and Hp of 0.6. All natural predators are  
183 continuously exposed to this predation fraction, on top of the longevity variable.  
184 The natural predators, as well as the pest insect, therefore disappear from the  
185 model either by natural death or due to predation by omitted species.

186 (ii) An, Af and Hp have multiple food sources besides Pp which is represented in the  
187 model by varying the An, Af and Hp food fractions between 0 and 1. The  
188 predation fractions therefore allow the predation of omitted species.

189 Other predators besides the three natural predators included in the model prey on *Cacopsylla*  
190 *pyri*. This effect is not included in the model, since the main aim of the model is to assess the  
191 specific effect of the loss of three specific natural predators on pest insect dynamics.

192 Despite the potential for beneficial effects for other natural predators upon removal of one  
193 natural predator, no such interspecies competition has been taken into account due to various  
194 reasons:

195 (i) different pest stages are attacked by different predators. Each species is modelled  
196 throughout their different life stages (egg, nymph, adult) and it is only that specific  
197 stage which is under predation from that natural predator.

198 (ii) there is an overlap in timing of occurrence for the three natural predators but their  
199 peak times differ considerably, thereby reducing the potential for competitive effects.

200 (iii) they differ in their nature (generalists/specialists) and generalists have the ability to  
201 switch to other food sources.



202 (iv) the pest insect is abundant and there is no lack of food resources for all predators.

203 Biodiversity loss is then quantified by the loss in species richness of natural predators which  
 204 is defined as the loss in the total number of species present, and assessed for its effect on the  
 205 species abundance of the pest insect, both expressed in absolute numbers per hectare. A total  
 206 of eight model scenarios (S1 – S8) were developed with S1 containing all species, S2 - S4  
 207 extinction of one natural predator, S5 - S7 extinction of two predators and S8 no natural  
 208 predators.

Predator species	Scenarios							
	S1	S2	S3	S4	S5	S6	S7	S8
PREDATOR 1: <i>Anthocoris nemoralis</i> (An)	x	x	0	x	0	x	0	0
PREDATOR 2: <i>Allothrombidium fuliginosum</i> (Af)	x	x	x	0	x	0	0	0
PREDATOR 3: <i>Heterotoma planicornis</i> (Hp)	x	0	x	x	0	0	x	0

209

210 Table 1: Schematic overview of the eight predator loss scenarios developed, indicating the  
 211 presence (x) or absence (0) of a natural predator for 8 scenarios (S1-S8). Scenario 1 (S1)  
 212 contains the pest insect and three natural predators, scenario 2 to 4 (S2 - S4) contains the pest  
 213 insect and two predators, scenario 5 to 7 (S5 - S7) contains the pest insect and one natural  
 214 predator and scenario S8 represents the scenario without predators.

215

216 The effect of a loss of species richness of natural predators is modeled for a one-year period  
 217 whereby the effect on pest suppression results in the absolute biological pest control loss  
 218  $BPC_{loss}$  composed as the sum of (i) an increase in pest insect abundance ( $Pp_I$ ) and (ii) a  
 219 decrease in predation ( $C_{loss}$ ) with

220 
$$BPC_{loss} = \sum(C_{loss}, Pp_I) > 0 \tag{eq.2}$$

221 with 
$$Pp_I = \sum(Ppe(S1) + Ppn(S1)) - \sum(Ppe(Sx) + Ppn(Sx)) < 0 \tag{eq.3}$$

222 and 
$$C_{loss} = C(S1) - C(Sx) > 0 \tag{eq.4}$$

223 Since eggs and nymphs are the main target for predation by predators,  $Pp_l$  calculates the  
 224 difference between S1 and each of the other scenarios (Sx) for the sum of all eggs  $Ppe$  and  
 225 nymphs  $Ppn$  appearing per year.

226 The relative loss in biological pest control  $RBPC_{loss}$  for S2-S8 compared to S1 is then

$$227 \frac{BPC_{loss}(Sx)}{BPC_{loss}(S1)} \quad (eq.5)$$

228 As eggs and nymphs are the main target for predation by predators,  $RBPC_{loss}$  is described in  
 229 terms of numbers for pest insect eggs and nymphs. These losses result in exponential  
 230 increases of numbers of adults over multiple generations per year. The latter numbers are then  
 231 linked to the occurrence of black pears through the identification of an ecological-economic  
 232 linking function.

### 233 **3.2 Identification of ecological-economic linking function**

234 Linking biological pest control losses, which result from the ecological simulation model,  
 235 with the economic model (section 3.3) is established by identifying a damage threshold  
 236 function that links the maximum pest density level  $\partial_{ppa}$  (adults  $ha^{-1}y^{-1}$ ) over all eight  
 237 scenarios with the yield quality decrease (black pear occurrence)  $\gamma$  (%). It is assumed that the  
 238 maximum  $\partial_{ppa}$  at any given time throughout the growing season will affect fruit russeting.  
 239 Experimental fruit research institutions recommend action to avoid ‘detectable damage’ when  
 240 monitoring reveals pest insect densities  $\partial_{ppa} > 1000$  adults per 10 beatings ( $\partial_{ETL} = 386 \cdot 10^6$   
 241 adults  $ha^{-1}$ )<sup>1</sup>. They then define the Economic Treshold Level (ETL) as the percentage of black  
 242 pears that is encountered at  $\partial_{ETL}$ .

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<sup>1</sup>  $\partial_{ppa} > 1000$  (adults per 3 shoots)\*20 (assume 5% caught)\*40 (shoots per tree)\* 1450 (trees per ha) =  $386 \cdot 10^6$  (adults per ha)

243 Since the shape of the damage threshold function is not known, two sets of four hypothesized  
 244 relationships are constructed to simulate the correlation between Ppa density levels  $\delta_{Ppa}$  ( $ha^{-1}y^{-1}$ )  
 245 and black pear occurrence  $\gamma$  (%) for the two assumptions made:

246 (i) Linear:  $\gamma_{lin} = \alpha \delta_{Ppa}$  (eq. 6)

247 (ii) Logistic:  $\gamma_S = \frac{k}{(1+(k-\delta_0/\delta_0))} * \exp^{r\delta_{Ppa}}$  (eq. 7)

248 (iii) Logarithm:  $\gamma_{log} = 1 - \exp^{-\delta_{Ppa}}$  (eq. 8)

249 (iv) Exponential:  $\gamma_{exp} = \exp^{\delta_{Ppa}}$  (eq. 9)

250 For the two sets of relationships, this results in a lower ( $\gamma_l$ ) and upper ( $\gamma_u$ ) percentage of black  
 251 pears for each scenario S1-S8 with:

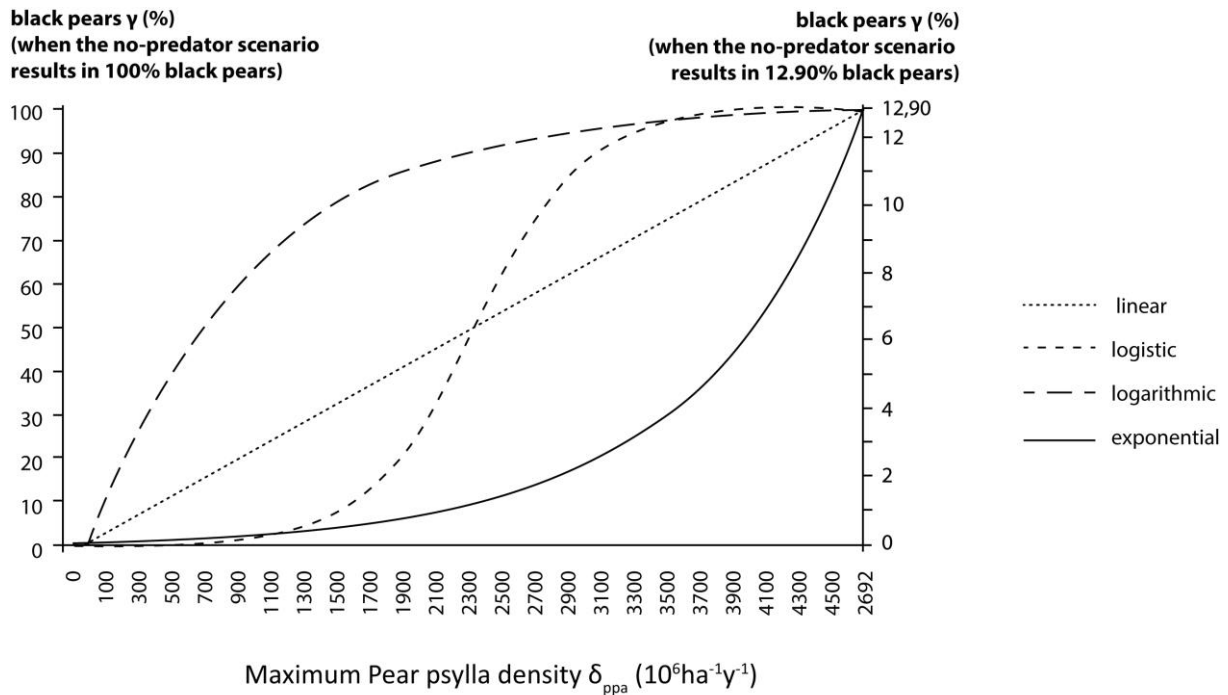
252  $\gamma_l = \min(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp})$  and  $\gamma_u = \max(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp})$  (eq. 10)

253 The first set of four hypothesized relationships assumes that the maximum  $\delta_{Ppa}$  in the no-  
 254 predator scenario (S8) results in 100% black pears. This results in an ETL of 0,28% and  
 255 32,02% black pears (figure 1 left vertical axis).

256 The second set of four hypothesized relationships assumes that the ETL for  $\delta_{Ppa}$  equal to  
 257  $386*10^6$  adults  $ha^{-1}$  equals 1% of black pears. This results in a potential maximum amount of  
 258 black pears of 12.90% at maximum  $\delta_{Ppa}$ <sup>2</sup> (figure 1 right vertical axis).

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<sup>2</sup> It is assumed that 'detectable damage' for the farmer equals 1% black pears.



259

260 Figure 1: shows the four hypothesized relationships  $\gamma_{lin}$ ,  $\gamma_S$ ,  $\gamma_{log}$ ,  $\gamma_{exp}$  that can exist between  
 261 the maximum pest density level  $\delta_{ppa}$  ( $10^6 \text{ha}^{-1} \text{y}^{-1}$ ) and the occurrence of black pears  $\gamma$  (%). For  
 262 each scenario, changing natural predator species results in changing pest density levels. The  
 263 damage threshold function then assesses the lower ( $\gamma_l$ ) and upper ( $\gamma_u$ ) percentage of black  
 264 pears encountered at the maximum pest density level  $\delta_{ppa}$  ( $10^6 \text{ha}^{-1} \text{y}^{-1}$ ). For the first set of  
 265 hypothesized relationships (left vertical axis), the maximum  $\delta_{ppa}$  in the no-predator scenario  
 266 (S8) results in 100% black pears (and therefore the ETL ranges between 0,28% and 32,02%  
 267 black pears). The second set of hypothesized relationships (right vertical axis) assumes that  
 268 the ETL equals 1% of black pears, resulting in a maximum potential percentage of black pears  
 269 of 12.90%.

### 270 3.3 Economic model construction

271 The economic model assesses the costs of a decrease in abundance and richness of natural  
 272 predators by analyzing the effects on yield quality decreases at farm scale calculating the  
 273 impact on (i) gross revenue and (ii) net income.

274 The gross revenue  $I_G$  for each scenario is defined as  $I_G = \sum(I_b, I_f)$  with  $b$  black pears and  $f$   
275 first class pears where  $I_b$  (respectively  $I_f$ ) represents the gross revenue with  $I_b = P_b * Q_b$   
276 (respectively  $I_f = P_f * Q_f$ ), with  $P_b$  (respectively  $P_f$ ) the price and  $Q_b$  (respectively  $Q_f$ ) the  
277 quantity. The farm net income for each scenario is defined as  $I_F = I_G - TC$  with  $TC$  the total  
278 costs,  $C_v$  the sum of all variable costs and  $C_f$  the sum of all fixed costs.

279 Annual accounting data on yields ( $\text{kg ha}^{-1}$ ), revenues ( $\text{€ ha}^{-1}$ ), variable costs ( $\text{€ ha}^{-1}$ ) and fixed  
280 costs ( $\text{€}$ ) for organic production and non-organic production (ANNEX C) were used from the  
281 Agricultural Monitoring Network (LMN) data (Van der Straeten, 2016), which are conform  
282 FADN<sup>3</sup> data collection procedures. The LMN dataset contains 53 non-organic pear farmers  
283 (accounting for 662 hectares) and provides annual accounting data for the period 2009-2014  
284 (Van der Straeten, 2016). Some numbers needed adjustment to represent organic production  
285 taking into account the following assumptions: (1) yields ( $\text{kg ha}^{-1}$ ) are 80% of non-organic  
286 production with  $\mu = 30092,27 \text{ kg ha}^{-1}$  and  $s = 3652,28^4$ , (2) organic management requires 30  
287 % more full-time equivalents (FTEs) with  $\mu = 4118,33 \text{ € ha}^{-1}$  and  $s = 352,15$  for non-organic  
288 production and  $\mu = 5353,83 \text{ € ha}^{-1}$  and  $s = 457,79$  for organic production (EC, 2013).

289 The parameters for which differences exist between organic and non-organic production are  
290 discussed here, for all other parameters we refer to ANNEX C. The yearly average selling  
291 price for 2009-2013 for all pear classes was  $\mu = 0.57 \text{ € kg}^{-1}$  ( $s = 0,16$ ) (Van der Straeten,  
292 2016) (with  $\mu = 0.55 \text{ € kg}^{-1}$  and  $s = 0,16$  for first class non-organic pears,  $\mu = 0.88 \text{ € kg}^{-1}$  ( $s =$   
293  $0,17$ ) for organic pears and  $\mu = 0.39 \text{ € kg}^{-1}$  ( $s = 0,12$ ) for black pears (personal communication  
294 Regional Auction Borgloon)).”

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<sup>3</sup> Farm Accounting Data Network

<sup>4</sup> With  $\mu$  the average and  $s$  the standard deviation

295 The Department of Agriculture and Fisheries<sup>5</sup> states that organic farmers receive 50% higher  
296 subsidies ( $\mu = 140 \text{ €ha}^{-1}$  ( $s = 55$ ) for non-organic and  $\mu = 210 \text{ €ha}^{-1}$  ( $s = 55$ ) for organic  
297 production). Costs for crop protection account for  $1579,83 \text{ €ha}^{-1}$  ( $s = 100,12$ ) for non-organic  
298 production and no costs are taken into account for organic production (Van der Straeten,  
299 2016).

300 Yields of black pears for each scenario were calculated based on the percentages of black  
301 pears encountered in the two sets of hypothesized relationships (section 3.2) and hence differ  
302 for all scenarios under analysis. For reasons of simplicity, other production factors (*e.g.*  
303 conservation costs, maintenance, packaging) are assumed equal for non-organic and organic  
304 production. The accounting data are imported into the risk analysis tool Aramis (@risk) and  
305 all economic parameters are stochastic variables to calculate a confidence interval for the  
306 gross revenues and the farm net income for each scenario S1-S8. Results from the risk  
307 analysis show the difference in gross revenues and the farm net income for a 95% confidence  
308 intervals for S1 to S7 for the two sets of relationships and are linked to yield quality decreases  
309 (black pear increases) that result directly from species richness losses.

### 310 **3.4 Model calibration**

311 We calibrated the dynamic simulation model for pest suppression in organic agriculture based  
312 on field data from one year for which most data points were available (2010). The units of  
313 field measurements (mean eggs/10 shoots) were transformed to yield model parameter units  
314 (absolute egg numbers per hectare), based on 33,84 shoots/tree on average, 5% of the eggs  
315 captured and 1714 trees per hectare (Van der Straeten, 2016). The reference model (S1)  
316 predicts both the peak density as well as the timing of the peaks relatively well (see ANNEX  
317 D).

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<sup>5</sup> <http://lv.vlaanderen.be/nl/bio/subsidies/hectaresteen-biologische-productiemethode-pdpo-iii> (last visited: 08-08-2016)

318 **4. Results**

319 **4.1 Losses of natural predators result in significant decreases for biological pest control**

320 ***RBPC<sub>loss</sub>***

321 The effect of a loss of species richness of natural predators on pest insect suppression revealed  
322 an increase in pest insect abundance ( $Pp_I$ ) (see eq.3) with decreasing predator numbers  
323 depending on the generalist/specialist nature of predation. For the reference scenario (S1),  
324 containing the 3 natural predators under investigation, the peak density of the sum of pest  
325 insect eggs and nymphs equaled  $1237 \cdot 10^6 \text{ha}^{-1}$ . S7 simulated the absence of *An* and *Af*  
326 revealing an increase to maximum peak density of 23888 ( $10^6 \text{ha}^{-1}$ ) or an increase rate of  
327 19.31. S2 (respectively S3; S4; S5; S6) simulates the absence of *Hp* (respectively  
328 *An*; *Af*; *An & Hp*; *Af & Hp*; *An & Af*) resulting in a peak density increase rate of 6.57  
329 (respectively 10.21; 8.82; 12.94; 19.31) revealing increases in eggs and nymphs absolute  
330 numbers to 2551 (respectively 12633; 8130; 10905; 16005) ( $10^6 \text{ha}^{-1}$ ).

331 Furthermore, for S1, 133 ( $10^6 \text{ha}^{-1}$ ) of the total eggs and nymphs (see section 4.1) are  
332 consumed in absolute terms (eq. 4). For S2 (respectively S4; S5; S6; S7) predation decreased  
333 to 113 (respectively 88; 78; 27; 4) ( $10^6 \text{ha}^{-1}$ ) equal to a reduction of 14.45 % (respectively  
334 33.71%; 96.98%; 79.61%; 41.43%) compared to predation in S1. For S3 an increase in  
335 predation to 290 ( $10^6 \text{ha}^{-1}$ ) was observed. This can be explained by the sharp increase in  
336 absolute numbers but when comparing relative numbers predation decreased from 10.72% in  
337 S1 to 2.30% for S3.

338 Summing the (i) increase in pest insects density and (ii) the decrease in predation resulted in  
339 an estimate for the biological pest control provided by differing combinations of natural  
340 predators (eq. 2). For S1, 10.72% of the total eggs and nymphs are consumed. For S2 to S7  
341 the relative biological pest control  $RBPC_{loss}$  reduced gradually to 4.45%, 2.30%, 1.08%,  
342 0.71%, 0.17% and 0.02%.

343 Predator losses resulted in exponential increases of numbers of pest insect adults over  
 344 multiple generations per year, and the maximum peak densities for pest insect adults  $\delta_{ppa}$   
 345 ( $10^6\text{ha}^{-1}\text{y}^{-1}$ ) increased from 146.92 for S1 to 379.77 (respectively 386.00; 1331.68; 1815.20;  
 346 2134.83; 2714.97; 4036.55) for S2 (respectively S3; S4; S5; S6; S7). The no predator scenario  
 347 (S8) resulted in adult pear psylla densities of 4692.23  $10^6\text{ha}^{-1}\text{y}^{-1}$ . Biological pest control losses  
 348 of eggs and nymphs therefore induced adult pest insect increases as compared to S1 of 258%  
 349 for S2, 263% for S3, 1236% for S4, 1453% for S5, 1847% for S6, 2747% for S7 and 3193%  
 350 for S8, thereby strongly supporting Hypothesis 1.

351 Next, the decrease in biological pest control, particularly the increase in adult pest insect  
 352 densities, was investigated for its potential to decrease pear quality in terms of % black pears  
 353 observed.

#### 354 4.2 Correlation between maximum pest insect density $\delta_{ppa}$ and black pear occurrence $\gamma$

355 For each scenario, the maximum pest density  $\delta_{ppa}$  ( $10^6\text{ha}^{-1}\text{y}^{-1}$ ) resulting in a lower ( $\gamma_l$ ) and  
 356 upper ( $\gamma_u$ ) percentage of black pears for the two sets of four hypothesized relationships  $\gamma_{lin}$ ,  
 357  $\gamma_s$ ,  $\gamma_{log}$ ,  $\gamma_{exp}$  was obtained. The results are presented in table 2.

(1)	(2)	(3)	(4)	(5)	(6)
Scenario	Max pest insect density $\delta_{ppa}$ ( $10^6\text{ha}^{-1}\text{y}^{-1}$ )	Loss of three predators causes 100% black pears		Loss of three predators causes 12.90% black pears	
		Lower % black pears ( $\gamma_l$ )	Upper % black pears ( $\gamma_u$ )	Lower % black pears ( $\gamma_l$ )	Upper % black pears ( $\gamma_u$ )
S1	146.92	0.14	13.66	0.01	1.08
S2	379.77	0.27	31.60	0.03	2.25
S3	1331.68	3.79	73.60	0.31	6.32
S4	1815.20	6.14	83.72	1.01	7.75
S5	2134.83	8.46	88.17	2.08	8.53
S6	2714.97	15.10	93.38	4.39	9.66
S7	4036.55	56.63	99.38	9.02	11.28
S8	4692.23	100.00	100.00	12.90	12.90

358



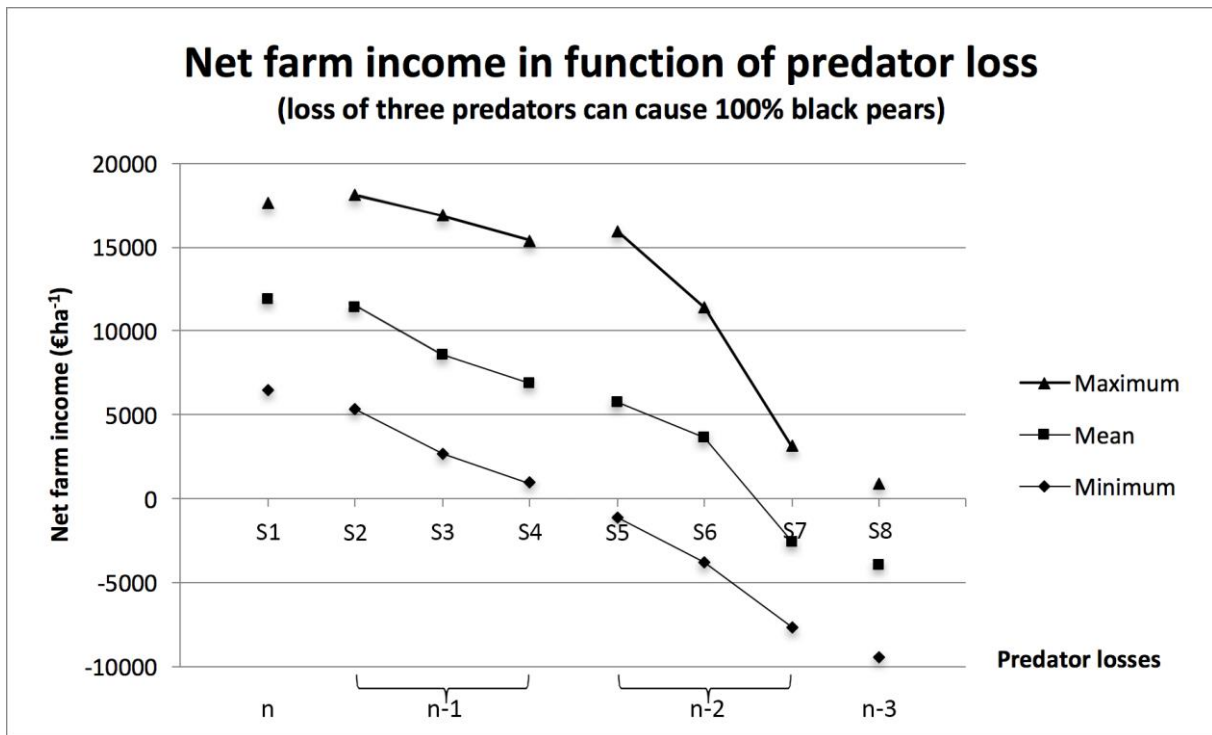
359 Table 2: the lower ( $\gamma_l$ ) and upper ( $\gamma_u$ ) percentage of black pears that can be encountered for  
360 the scenarios under investigation (S1-S8). Column (2) represents the maximum adult pest  
361 insect densities  $\delta_{ppa}$  that are expected for each scenario. Column (3) and (4) represent the  
362 lower ( $\gamma_l$ ) and upper ( $\gamma_u$ ) percentage of black pears under the assumption that the overall  
363 maximum  $\partial_{ppa}$  in the no-predator scenario S8 results in 100% black pears. Column (5) and  
364 (6) represent the lower ( $\gamma_l$ ) and upper ( $\gamma_u$ ) percentage of black pears under the assumption  
365 that the ETL equals 1% of black pears, corresponding to a potential maximum of black pears  
366 of 12.90%.

### 367 **4.3 Economic impact of natural predator losses**

368 The economic impact of a loss of natural predators is first discussed for the first set of  
369 hypothesized relationships, which assumed that the loss of three predators could result in  
370 100% black pears.

371 The gross revenues for S1 ranged between 12856 €ha<sup>-1</sup> and 23835 €ha<sup>-1</sup> with a mean of 18261  
372 €ha<sup>-1</sup>. The reduction in mean gross revenues for S2 (respectively S3-S8) constituted 2.9%  
373 (respectively 18.41%, 27.49%, 33.69%, 45.10%, 79,34% and 86.98%) resulting in an average  
374  $I_G$  of 217731€ha<sup>-1</sup> (respectively 14899 €ha<sup>-1</sup>, 13241 €ha<sup>-1</sup>, 12109 €ha<sup>-1</sup>, 10026 €ha<sup>-1</sup>, 3773 €ha<sup>-1</sup>  
375 <sup>1</sup> and 2377 €ha<sup>-1</sup>). Hence, for the loss of the three predators, the average gross revenues  
376 decreased from 18261 €ha<sup>-1</sup> for S1 to 2377 €ha<sup>-1</sup> for S8. The net farm income (figure 2) also  
377 reveals large losses under the assumption that the loss of three predators can yield 100% black  
378 pears. The mean farm income  $I_F$  for S1 with three natural predators (n) was 11921 €ha<sup>-1</sup> and  
379 decreased to -3962 €ha<sup>-1</sup> for S8 with the loss of three predators (n-3).

380



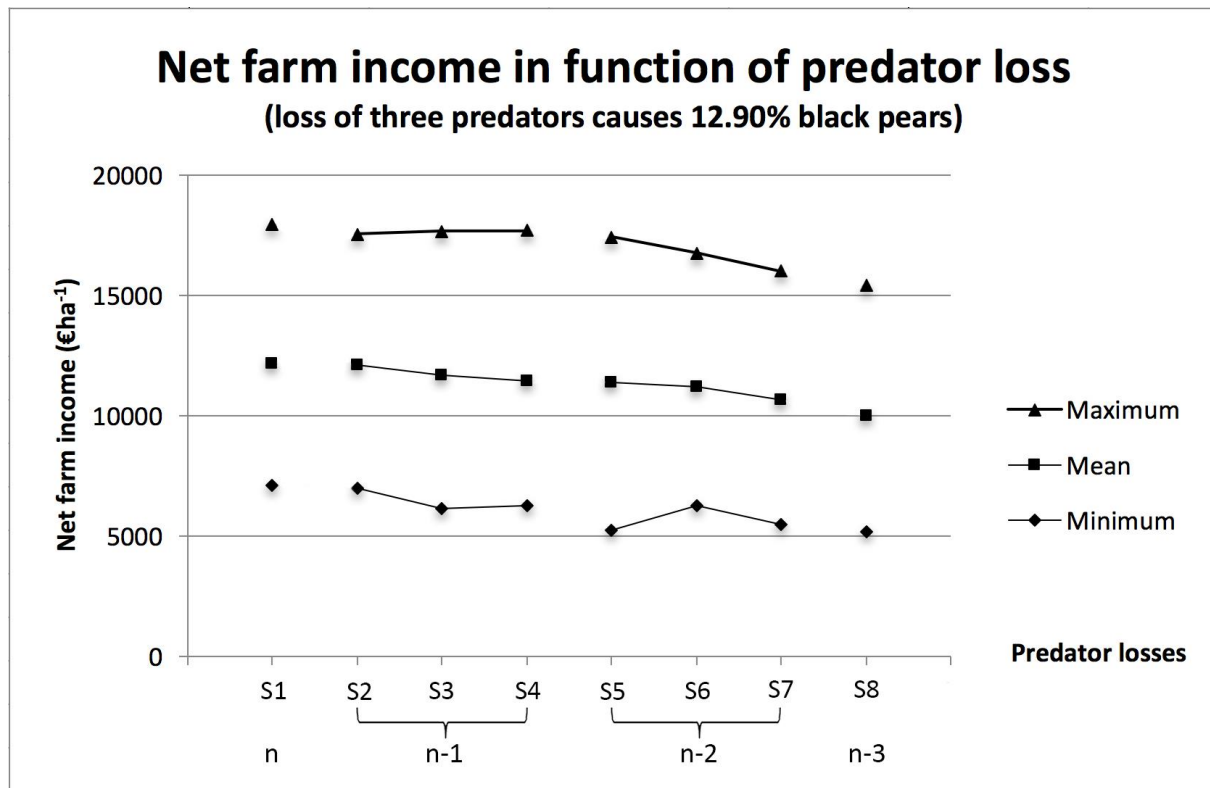
381

382 Figure 2 represents the effect of a loss of one or more natural predator on the net farm income  
 383  $I_F$  (€ha<sup>-1</sup>) under the assumption that the loss of all three predators can result in 100% black  
 384 pears (with n all predators present for S1; n-1 the loss of one predator for S2, S3 and S4; n-2  
 385 the loss of two predators for S5, S6 and S7; and n-3 the loss of all three predators for S8). The  
 386 95% confidence intervals are represented as the minimum and the maximum and are plotted  
 387 together with the mean for each scenario. The graph shows that for the loss of all three  
 388 predators, the mean net farm income for S1 reduces from 11921 €ha<sup>-1</sup> to -3962 €ha<sup>-1</sup> for S8.

389 Next, the economic impact of a loss of natural predators is discussed for the second set of  
 390 hypothesized relationships, which assumed that the loss of three predators could result in an  
 391 overall maximum of 12.90% black pears.

392 Under this assumption, the mean gross revenues  $I_G$  for S1 reduce from 18500 €ha<sup>-1</sup> to 16313  
 393 €ha<sup>-1</sup> for S8, constituting a loss of 2187 €ha<sup>-1</sup> or 11,82 % for the loss of all three predators.  
 394 The mean net farm income  $I_F$  (figure 3) reduces from 12161 €ha<sup>-1</sup> for S1 to 9974 €ha<sup>-1</sup> for S8,  
 395 also constituting a loss of 2187 or 17,98 % for the loss of all three predators. The losses on a

396 per hectare basis vary between 1941 €ha<sup>-1</sup> and 2531 €ha<sup>-1</sup> for S1 compared to S8. All the  
 397 results for the gross revenues and the net farm income are presented in table 3.



398

399 Figure 3 represents the effect of a loss of one or more natural predator on the net farm income  
 400  $I_F$  (€ha<sup>-1</sup>) under the assumption that the ETL equals 1% black pears (with n all predators  
 401 present for S1; n-1 the loss of one predator for S2, S3 and S4; n-2 the loss of two predators for  
 402 S5, S6 and S7; and n-3 the loss of all three predators for S8). The 95% confidence intervals  
 403 are represented as the minimum and the maximum and are plotted together with the mean for  
 404 each scenario. The graph shows that for the loss of all three predators, the mean net farm  
 405 income for S1 reduces from 12161 €ha<sup>-1</sup> for S1 to 9974 €ha<sup>-1</sup> for S8.

Scenario	Loss of three predators causes 100% black pears				Loss of three predators causes 12.90% black pears			
	min	max	mean	stdev	min	max	mean	stdev
GROSS REVENUES (€ha <sup>-1</sup> )								
S1	12856,3	23834,94	18260,68	1944,92	13227,04	24280,28	18499,78	2028,19
S2	11739,73	24203,07	17730,51	2043,76	13207,21	23877,41	18410,92	1997,01
S3	9234,34	23200,83	14898,57	2329,98	12476,74	24158,11	18040,56	1921,93

S4	7410,81	21788,05	13241,45	2487,25	12788,47	23938,64	17789,06	1963,86
S5	5075,61	22270,21	12108,94	2512,07	11812,83	23620,97	17735,32	1960,43
S6	2692,53	17836,26	10025,62	2565,14	12567,21	22959,54	17516,96	1910,06
S7	-1095,99	9653,07	3773,27	1749,26	11806,73	22142,97	16994,41	1868,49
S8	-3128,91	7227,23	2377,36	1778,3	11591	21634,32	16313,27	1840,14
NET FARM INCOME (€ha <sup>-1</sup> )								
S1	6440,26	17621,08	11921,49	1956,64	7082,07	17908,47	12160,6	2032,66
S2	5384,04	18080,43	11391,35	2053,67	6957,19	17537,69	12071,74	2001,95
S3	2688,18	16904,73	8559,41	2332,45	6120,66	17660,34	11701,39	1935,03
S4	945,09	15384,3	6902,27	2487,09	6272,24	17685,12	11449,9	1977,06
S5	-1096,02	15937,79	5769,77	2505,61	5250,49	17396,57	11396,15	1971,96
S6	-3753,8	11385,11	3686,44	2567,32	6247,29	16741,57	11177,8	1912,34
S7	-7651,83	3138,49	-2565,92	1751,27	5460,22	15988,82	10665,26	1868,96
S8	-9443,79	878,18	-3961,8	1784,15	5141,26	15377,25	9974,1	1836,61

406 Table 3: shows the minimum, maximum, mean and standard deviation for the gross revenues  
407 (€ha<sup>-1</sup>) and the net farm income (€ha<sup>-1</sup>) for scenario S1 to S8 under the assumption that the  
408 loss of three predators causes 100% of black pears, and under the assumption that the loss of  
409 three predators causes a maximum of 12.90% of black pears.

410 For both sets of hypothesized relationships, the net farm income reduces when natural  
411 predators are lost, thereby supporting Hypothesis 2.

#### 412 4.4 An indirect use value for the presence of natural predators

413 The losses with respect to the gross revenue show results very similar to the losses with  
414 respect to the net farm income but differ greatly between the two sets of hypothesized  
415 relationships. Under the assumption that the overall maximum  $\partial_{ppa}$  in the no-predator  
416 scenario S8 results in 100% black pears, gross revenue for the removal of one predator  
417 indicate a loss of  $I_G$  between 530.17 €ha<sup>-1</sup> and 5019.23 €ha<sup>-1</sup>. A loss of two natural predators  
418 would result in  $I_G$  losses between 6151.74 €ha<sup>-1</sup> and 14487.41 €ha<sup>-1</sup> and the removal of all  
419 predators caused a loss of 15883.32 €ha<sup>-1</sup>. With regards to the net farm income  $I_F$ , results are  
420 in the same order of magnitude with the loss of one natural predator resulting in a loss of  $I_F$   
421 between 530.14 and 5019.22 (€ha<sup>-1</sup>). A loss of two natural predators would result in  $I_F$  losses

422 between 6151.72 €ha<sup>-1</sup> and 14487.41 €ha<sup>-1</sup> and the removal of all predators caused a loss of  
 423 15883.29 €ha<sup>-1</sup>.

424 Under the assumption that the loss of natural predators can cause a maximum of 12.90%  
 425 black pears, gross revenue reductions for the removal of one predator indicate a loss of  $I_G$   
 426 between 88.86 €ha<sup>-1</sup> and 710.72 €ha<sup>-1</sup>. A loss of two natural predators would result in  $I_G$  losses  
 427 between 764.46 €ha<sup>-1</sup> and 1505.37 €ha<sup>-1</sup> and the removal of all predators caused a loss of  
 428 2186.51 €ha<sup>-1</sup>. With regards to the farm income  $I_F$ , results are again in the same order of  
 429 magnitude with the loss of one natural predator resulting in a loss of  $I_F$  between 88.86 €ha<sup>-1</sup>  
 430 and 710.70 €ha<sup>-1</sup>. A loss of two natural predators would result in  $I_F$  losses between 764.46  
 431 €ha<sup>-1</sup> and 1495.34 €ha<sup>-1</sup> and the removal of all predators caused a loss of 2186.50 €ha<sup>-1</sup>. The  
 432 net farm income losses for both hypotheses are presented in table 4.

Scenario	Loss of three predators causes 100% black pears	Loss of three predators causes 12.90% black pears
	Net farm income losses (€ha <sup>-1</sup> )	Net farm income losses (€ha <sup>-1</sup> )
S2	530.14	88.86
S3	3362.08	459.21
S4	5019.22	710.70
S5	6151.72	764.45
S6	8235.05	982.80
S7	14487.41	1495.34
S8	15883.29	2186.50

433 Table 4: shows the losses to the net farm income (€ha<sup>-1</sup>) for all scenarios S1 – S8 under the  
 434 assumption that a loss of three predators can cause 100% black pears and under the  
 435 assumption that the loss of three predators causes 12.90% black pears.

## 436 5. Discussion

437 The results support [Hypothesis 1](#) that a decrease in natural predators causes a significant  
 438 decrease in the provisioning of the ecosystem service biological pest control from 10.72% for  
 439 S1 to a minimum of 1.08% for the loss of one predator, further reducing to 0.02% for the loss

440 of three predators, or equal to a total potential reduction with a factor 536 for the loss of two  
441 species. Also, the analysis showed that a reduction in natural predators could considerably  
442 reduce the quality of marketable agricultural production and that this depends highly on the  
443 hypotheses used. The first set of hypothesized relationships assumed that the total yield could  
444 consist of black pears only if all three predators would no longer occur in the agro-ecosystem.  
445 The second set of hypothesized relationships assumed that the Economic Threshold Level  
446 (ETL) equaled 1% of black pears, fixing the maximum potential of black pears upon losing  
447 the three predators at 12.90%. The economic results for the first set revealed losses of up to  
448 15883 €ha<sup>-1</sup> for the loss of three predators, making pear production financially unviable. The  
449 results for the second set reveal losses of up to 2186 €ha<sup>-1</sup> when losing all three predators.  
450 Considering the fact that pear psylla has other natural predators (e.g. *Theridion spp.*,  
451 *Philodromus spp.*, members of the Araneidae and the seven-spot ladybird) (Erlor, 2004)), it  
452 seems likely that the combined effect of all predators keeps pest densities within economic  
453 threshold levels, thereby supporting [Hypothesis 2](#) that the three predators under analysis could  
454 induce a maximum of 12.90% of lower quality pears. On a per hectare basis, the occurrence  
455 of lower quality yields could therefore decrease gross revenues or net farm income with 88.86  
456 € to 2186.5 €. For the pear production sector in Flanders in 2011, this would mean an indirect  
457 use value of 0,68 million € for one predator and 16.63 million euros for three predators.  
458 Considering that the gross revenues for the sector totaled on average 163 million euros for the  
459 period 2009-2013, the contribution of the predators accounts for 0,41% to 10.2% of the  
460 sectors' gross revenues.

461 By employing the ecological role of species through the development of an ecological  
462 simulation model, combined with a production function technique and a direct market  
463 valuation approach, we believe that economic values of non-marketable species could be  
464 estimated more realistically as compared to employing WTP estimates. This is largely due to

465 the fact that the importance of lesser-known species to perform valuable ecological services is  
466 not known by the general public, and therefore this might impact the valuation of these  
467 species. Therefore, according to Hypothesis 3, we are convinced that the methodology applied  
468 here could contribute to the introduction of alternative methods for the valuation of  
469 biodiversity based on the ecological role of species. Research from Boerema et al. (2016)  
470 supports this hypothesis since: (i) their results show that, up until now, there was no paper on  
471 biological control examining the whole ES ‘cascade’, (ii) it is stated that *‘measures of*  
472 *ecosystem functions are stronger as they give a better idea of ES supply and how this*  
473 *fluctuates spatiotemporally’* as compared to *‘simple measures or indicators of biodiversity*  
474 *and population size’*, (iii) they recommend that net value, defined as *“the market price*  
475 *corrected for production costs...”, “is a more appropriate measure to determine the added*  
476 *value”* and last, (iv) *“To quantify the sustainable supply of an ES, it is necessary to quantify*  
477 *the properties and functions of an ecosystem (ecological side of the cascade), whereas to*  
478 *quantify the importance to society it is necessary to understand and quantify the benefit to*  
479 *society (socio-economic side). Many researchers are only considering one side of this*  
480 *cascade and therefore are not succeeding in understanding the whole picture.(Boerema et al.,*  
481 *2016)”*

482 The results of applying a functional role-based approach, shows that losses of natural  
483 predators for pear production could significantly reduce a farmer’s income. The results of this  
484 analysis need to be viewed within a wider framework of (1) the partitioning of biodiversity  
485 effects on function into species richness, species composition and abundance effects and (2)  
486 functional redundancy.

487 First, in this analysis the number of predators was reduced, which also reduced total predator  
488 biomass. The resulting effects on net farm income can therefore not solely be attributed to a  
489 decline in species richness. In Winfree et al. (2015) biodiversity effects on function were split

490 into five additive components according to the Price equation: species richness losses (RICH-  
491 L), species richness gains (RICH-G), species composition effects that capture any non-  
492 randomness with respect to function of the species that were lost (COMP-L) and of the  
493 species that were gained (COMP-G) and changes in abundance of species that are always  
494 present (ABUN) (Fox, 2006; Fox&Harpole, 2008; Fox & Kerr, 2012). Winfree et al. (2015)  
495 stated that “*abundance fluctuations of dominant species in real world conditions drives*  
496 *ecosystem service delivery, whereas richness changes were relatively unimportant because*  
497 *they primarily involved rare species that contributed little to function.*” Also, Winfree et al.  
498 (2015) revealed that “*...random loss of species has (or would have) large functional effects,*  
499 *and that the identity of the species that are lost is also important*”. Although we cannot be  
500 sure on the nature of the losses and how much each component contributes to the effects on  
501 net farm income, this does not undermine the overall effect that a reduction in the number of  
502 predators and their biomass can potentially have on farm income.

503 Second, the indirect use value for the presence of natural predators depends highly on the  
504 functional redundancy of these species. The concept of functional redundancy is based on the  
505 principle that some species perform similar roles in ecosystems and might therefore be  
506 substitutable with little impact on ecosystem processes (Lawton and Brown, 1993). Therefore  
507 the effect of species loss depends on (i) the range of functions and the diversity of species  
508 within a functional group, (ii) the relative partitioning of variance in functional space between  
509 and within functional groups, and (iii) the potential for functional compensation of the species  
510 (Rosenfeld, 2002). Whilst *Anthocoris nemoralis*, *Allothrombidium fuliginosum* and  
511 *Heterotoma planicornis* are all natural predators of *Cacopsylla pyri*, one might assume that  
512 they are functionally redundant and that the impact of the loss of one natural predator does not  
513 significantly alter the impact on biological pest control. However, it is argued here that  
514 although providing the same function they are not functionally redundant due to (i) exertion



515 of ecological function occurring on different time scales: species that occur on critical timings  
516 *e.g.* when high pest density levels are expected, can be considered of higher functional  
517 importance, (ii) differences in duration of ecological function, (iii) differences in degree of  
518 specialization: whilst some species thrive in a wide variety of environmental conditions, some  
519 require specific conditions for survival, rendering them less resilient to external shocks (iv)  
520 differing impacts on other species in the ecosystem due to predation preferences: generalists  
521 versus specialists, (v) attacking different pest stages and (vi) the absolute numbers of  
522 predators. The relationship between functional redundancy and economic value of species can  
523 be represented as an exponential decline whereby the marginal value of the loss of the first  
524 species is small and the loss of the last species is infinite. Therefore, the economic values  
525 represented in this analysis do not reflect values on either of the extreme ends of the marginal  
526 value curve. It is argued here that although species perform the same function, they are not  
527 functionally redundant, that the loss of one species or abundance of the species can  
528 significantly alter the provisioning of ecological functions and that attributing an indirect use  
529 value to the loss of one species is justified. Furthermore, our simulation model does  
530 effectively take into account differences in timing, duration and prey preference. The indirect  
531 use value therefore reflects the functional differences and effectively takes into account the  
532 importance of the different species for the biological pest control of *Cacopsylla pyri*.  
533 Finally, of equal importance in this analysis is the fact that the economic valuation of  
534 biodiversity is regarded as just one of the aspects that could strengthen the argument in favor  
535 of biodiversity conservation and hence needs to be viewed within a wider framework of  
536 biodiversity valuation. Biodiversity is by nature a multidimensional concept and expressing  
537 the importance of biodiversity in economic terms does by no means exclude the presence of  
538 an intrinsic value (Feest et al., 2010). It is our opinion that choosing the most effective  
539 valuation methodology depends both on the context as well as on the species involved. When

540 it considers species with a high socio-cultural value, economic valuation may not be needed  
541 and its socio-cultural value alone may be sufficient to ensure protection. However, when it  
542 concerns species that do not possess such an explicit socio-cultural value (as it in our case  
543 with insects or natural predators) additional arguments such as economic valuation may  
544 strengthen the argument in favor of conservation. Within this wider framework of valuation, it  
545 is our belief that *if* an economic argument for biodiversity conservation is needed, an  
546 ecological function approach may reveal more objective values than the application of stated  
547 preference techniques, due to the complex nature of the biodiversity and ecosystem services  
548 concept on behalf of the general public.

#### 549 **4 Conclusion**

550 It is the aim of this paper to emphasize the importance of healthy agro-ecosystems, not only  
551 for the purpose of food production but also for the contribution to the farmer's income. It is  
552 stressed here that effective valuation of biodiversity can include both intrinsic as well as  
553 economic arguments but that, in order to take into account the effect of biodiversity losses in  
554 economic arguments, it is imperative that the ecological function is taken into account. This  
555 implies some challenges. First, modeling real systems is rarely simple and the reality shows a  
556 great variability both in ecological as well as in economic parameters. The analysis provided  
557 here therefore provides an indication of the effect of the loss of species on the provisioning of  
558 biological pest control and on the decrease of quality. Furthermore, the authors point out the  
559 limitations of the use of stated preference techniques when valuing complex concepts such as  
560 biodiversity and ecosystem functioning. Willingness To Pay may not reflect the true  
561 ecological service that is provided by beneficial insects, since only a part of the general public  
562 has limited knowledge of the concept. Our analysis therefore provides an alternative  
563 methodology for the valuation of biodiversity, taking into account the ecological function of  
564 species in the ecosystem, hereby revealing values linked to marketable agricultural outputs.

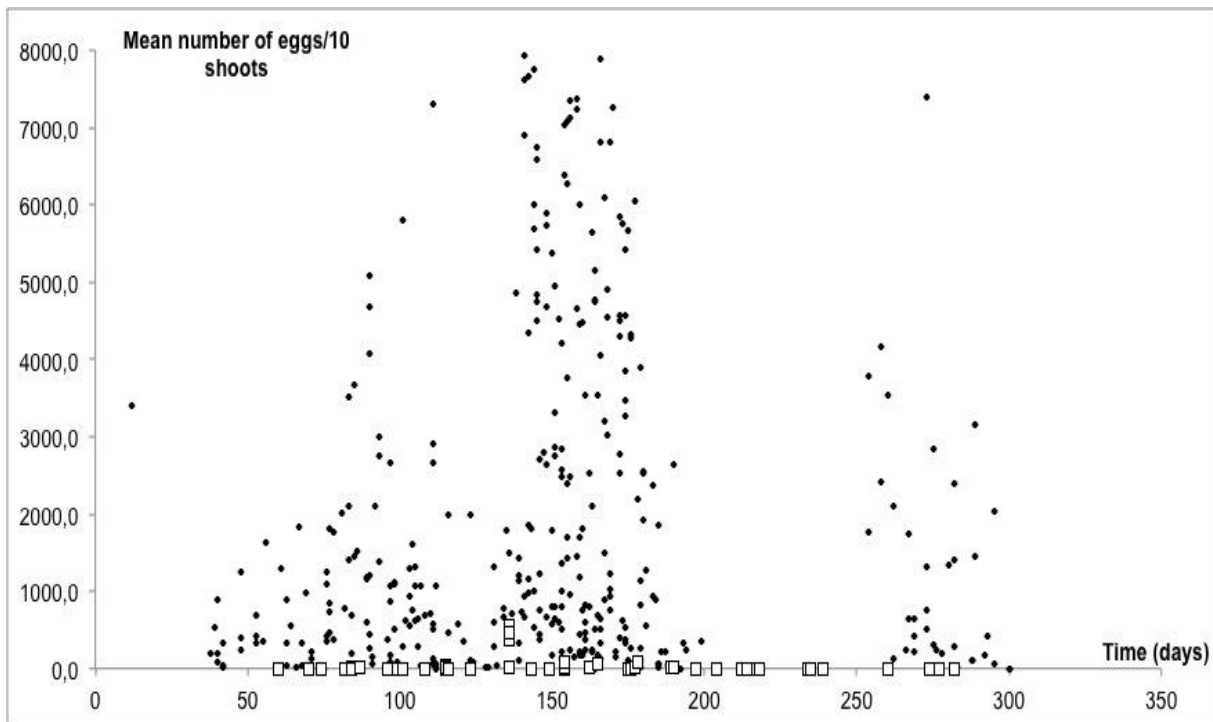
565 Using an ecological function based approach, values for the presence of species diversity  
566 could be considered more objective compared to stated preference methods. These values  
567 could be supplied to inform policy makers about the importance of including biodiversity  
568 effects and providing a justification for the opportunity costs encountered.

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573 providing relevant data and insights into the complex interplay between pest insects, natural  
574 predators and human impacts from fertilizers and pesticide use.

575 ANNEX A

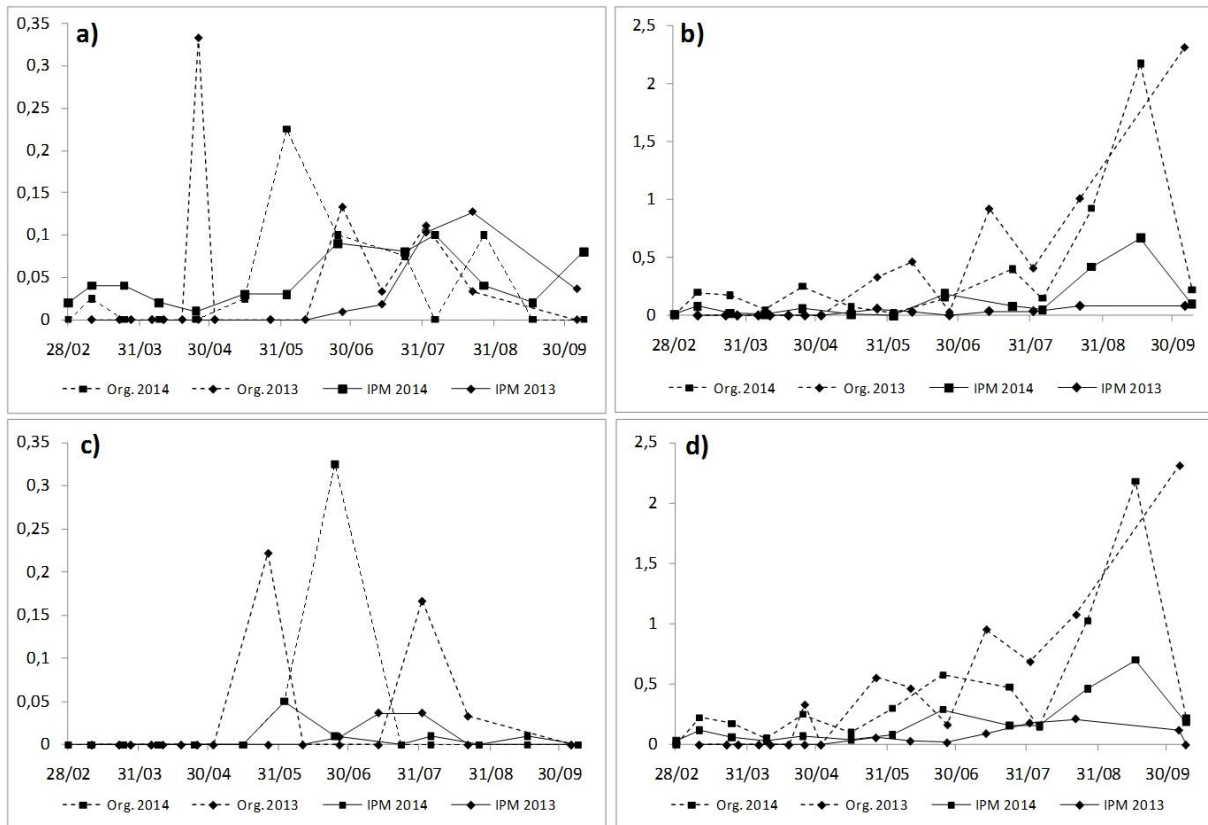
576 Each field test sampled pear psylla eggs and nymphs on multiple days. The first dataset  
577 comprises a total number of 111 field tests in *conférence* pear orchards (7 in organic  
578 production and 104 in IPM (Integrated Pest Management)) on 15 different plots (8 in IPM and  
579 7 in organic production) performed in Haspengouw (Belgium) for consecutive years of  
580 measurement (2004-2014). Data obtained from the plots under organic management were  
581 sampled in 2013 and 2014. Using the beating-tray method (3 beatings x 3 branches x 10 trees  
582 plot<sup>-1</sup>), the nymph stages N1 to N5 are collected in a beating tray and counted (for a review of  
583 sampling methods see Jenser et al., 2010). A visual count is performed on newly developed  
584 shoot tips to assess the presence of eggs (visual counts are performed for 2 shoots per tree for  
585 4-10 trees per plot segment with 4 plot segments per plot). Adult counts were performed  
586 sporadically with the beating-tray method but have not been included in the data due to its  
587 susceptibility to bias caused by adult mobility and the dependency on weather conditions. The  
588 mean counts of eggs per ten shoots are pooled for all consecutive years and plotted in figure  
589 A.1. For the years of measurement, it can be observed that counts in IPM orchards are  
590 considerably higher than counts in organic orchards.



591

592 Figure A.1: pooled sample of mean numbers of pear psylla eggs per ten shoots collected  
 593 between 2004 and 2014 (◆IPM; □ organic).

594 In 2013 and 2014, counts for the presence of beneficial insects were been performed between  
 595 February and October in IPM and organic *conference* pear orchards. Linear transects of three  
 596 pitfall traps ( $r=0.2m$ ) per 50m per pear row for three rows per plot were filled with water and  
 597 detergent and left standing for 7 days. Emptying of the containers produced members of the  
 598 order of the Aranea, Acari, Coleoptera, Hemiptera and Neuroptera. Figure 2 represents the  
 599 pooled counts for a selection of the species in the samples collected based on the importance  
 600 of their functional role as natural predators of pear psylla *Cacopsylla pyri* (Homoptera:  
 601 psylliidae): *Anthocoris nemoralis* (Heteroptera: anthocoridae), *Allothrombidium fuliginosum*  
 602 (Acari: trombidiiidae) and *Heterotoma planicornis* (Hemiptera: miridae).



603

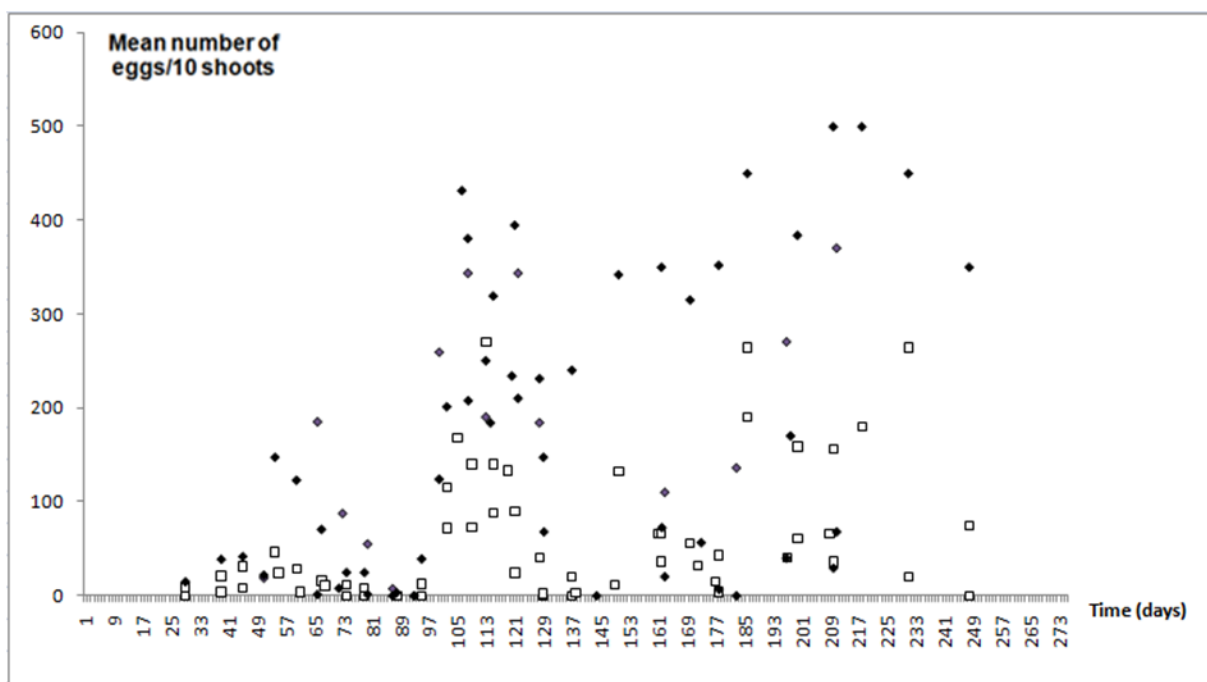
604 Figure A.2: absolute number of individuals per sample for a) *Anthocoris nemoralis*, b)  
 605 *Allothrombidium fuliginosum*, c) *Heterotoma planicornis* and d) sum of the absolute numbers  
 606 of a, b and c.

607 Figure A.2 shows (i) the difference in abundance levels of the three natural predators and (ii)  
 608 the timing of occurrence. These two factors combined with their generalist/specialist nature  
 609 determine the importance as natural pest controllers. Whilst *Allothrombidium fuliginosum* (b)  
 610 may be abundant, it is not a specialist and it preys on other insects than *Cacopsylla pyri*.  
 611 *Anthocoris nemoralis* (a) is less abundant but is a specialist and therefore qualifies as a rare  
 612 but highly effective pest controller. Last, *Heterotoma planicornis* (c) is both rare and a  
 613 generalist and therefore differs from the two other predators.

614 Whilst the predators differ in terms of their generalist/specialist nature and their levels of  
 615 abundance, they also differ in the timing of occurrence. Whilst *Anthocoris nemoralis* (a) is  
 616 mainly encountered during the first half of the year, *Heterotoma planicornis* (c) is mainly

617 found in the middle of the year whilst *Allothrombium fuliginosum* (b) is the main predator at  
 618 the end of the year. So even when *Anthocoris nemoralis* (a) can be considered a rare species,  
 619 they are highly effective and important given their ability to suppress the build-up of the pest  
 620 population in the beginning of the season. The removal of one individual in the beginning of  
 621 the year has an exponential effect on the pest insect density later that year, making the  
 622 presence of predators in the beginning essential for controlling pest outbreaks. Equally so,  
 623 *Allothrombium fuliginosum* (b) is an abundant species occurring at the end of the season,  
 624 suppressing the population before the build-up in the new season.

625 The second dataset was obtained from field test performed every two weeks for the period  
 626 2010-2011 on 14 plots (7 in organic production and 7 in IPM) in Hageland (BE) and  
 627 Gelderland and Limburg (NL). The same techniques were used to assess mean egg numbers  
 628 and larvae numbers (visual scouting and beating tray method).



629  
 630 Figure A.3: Pooled sample of mean numbers of pear psylla eggs per ten shoots (◆ IPM; □  
 631 organic).

632 Data obtained from the plots under organic management were sampled in 2013 and 2014.  
633 Using the beating-tray method (3 beatings x 3 branches x 10 trees plot<sup>-1</sup>), the nymph stages  
634 N1 to N5 are collected in a beating tray and counted (for a review of sampling methods see  
635 Jenser et al., 2010). A visual count is performed on newly developed shoot tips to assess the  
636 presence of eggs (visual counts are performed for 2 shoots per tree for 4-10 trees per plot  
637 segment with 4 plot segments per plot). Adult counts were performed sporadically with the  
638 beating-tray method but have not been included in the data due to its susceptibility to bias  
639 caused by adult mobility and the dependency on weather conditions. The mean counts of eggs  
640 per ten shoots were pooled for all consecutive years and plotted.

641



## ANNEX B

Parameter	Model component	Initial value
(1) Initialization 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 b presents initial parameter values for Pp, An, Af, Hp for eggs (e), nymphs (n) and adults (a)

## ANNEX C

<b>NON-ORGANIC PRODUCTION</b>				
	Mean	stdev	95% confidence interval	
Total yield (kg $ha^{-1}$ )	37615,33	4565,36	33962,29	41268,38
Selling price all pears(€kg $^{-1}$ )	0,57	0,16	0,44	0,70
Selling price 1st class pears(€kg $^{-1}$ )	0,55	0,16	0,42	0,68
Selling price black pears(€kg $^{-1}$ )	0,39	0,12	0,29	0,49
<b><u>GROSS REVENUES (€ha<math>^{-1}</math>)</u></b>				
Main products	20247,67	3654,52	17323,44	23171,89
Plantation growth	207,00	34,05	179,75	234,25
Other products	96,83	127,62	-5,28	198,95
Subsidies	140,00	55,00	95,99	184,01
<b><u>VARIABLE COSTS (€ha<math>^{-1}</math>)</u></b>				
Fertilizers	362,33	39,51	330,72	393,94
Crop protection	1579,83	100,12	1499,72	1659,94
Seasonal wages and labour	4118,33	352,15	3836,56	4400,11
Maintenance, packaging and preservation	1329,33	62,64	1279,21	1379,46
Energy	799,33	85,55	730,88	867,79
Other variable costs	260,50	23,68	241,55	279,45
<b><u>FIXED COSTS (€)</u></b>				
Lease/rent	463,00	76,87	401,49	524,51
Amortization fixed equipment	1274,17	35,72	1245,59	1302,75
Amortization buildings	1033,50	85,93	964,74	1102,26
Amortizations plantations	392,83	8,77	385,81	399,85
Interests	1450,00	31,25	1424,99	1475,01
General corporate costs	1692,67	275,62	1472,13	1913,21
<b>ORGANIC PRODUCTION</b>				
	Mean	stdev	95% confidence interval	
Total yield (kg $ha^{-1}$ )	30092,27	3652,28	27169,83	33014,70
Selling price all pears(€kg $^{-1}$ )	0,57	0,16	0,44	0,70
Selling price 1st class pears(€kg $^{-1}$ )	0,88	0,17	0,74	1,02
Selling price black pears(€kg $^{-1}$ )	0,39	0,12	0,29	0,49
<b><u>GROSS REVENUES (€ha<math>^{-1}</math>)</u></b>				
Main products				
Plantation growth	207,00	34,05	179,75	234,25
Other products	96,83	127,62	-5,28	198,95
Subsidies	210,00	105,00	125,98	294,02
<b><u>VARIABLE COSTS (€ha<math>^{-1}</math>)</u></b>				
Fertilizers	362,33	39,51	330,72	393,94
Crop protection	0,00	0,00	0,00	0,00
Seasonal wages and labour	5353,83	457,79	3836,56	5635,61

Maintenance, packaging and preservation	1329,33	62,64	1279,21	1379,46
Energy	799,33	85,55	730,88	867,79
Other variable costs	260,50	23,68	241,55	279,45
<b><u>FIXED COSTS (€)</u></b>				
Lease/rent	463,00	76,87	401,49	524,51
Amortization fixed equipment	1274,17	35,72	1245,59	1302,75
Amortization buildings	1033,50	85,93	964,74	1102,26
Amortizations plantations	392,83	8,77	385,81	399,85
Interests	1450,00	31,25	1424,99	1475,01
General corporate costs	1692,67	275,62	1472,13	1913,21

642 (Van der Straeten, 2016; Personal communication from Regional Auction Borgloon)

643 Table C presents annual accounting data on yields ( $\text{kg ha}^{-1}$ ), revenues ( $\text{€ ha}^{-1}$ ), variable costs  
644 ( $\text{€ ha}^{-1}$ ) and fixed costs ( $\text{€}$ ) for non-organic production and organic production from the  
645 Agricultural Monitoring Network (LMN) data (Van der Straeten, 2016), which are conform  
646 FADN<sup>6</sup> data collection procedures. The LMN dataset contains 53 non-organic pear farmers  
647 (accounting for 662 hectares) and provides means, standard deviations and the 95%  
648 confidence interval based on annual accounting data for the period 2009-2014 (Van der  
649 Straeten, 2016). Some numbers were adjusted to represent organic production taking into  
650 account the following assumptions: (1) yields ( $\text{kgha}^{-1}$ ) are 80% of non-organic production  
651 with  $\mu = 30092,27 \text{ kgha}^{-1}$  and  $s = 3652,28^7$ , (2) organic management requires 30 % more full-  
652 time equivalent (FTEs) with  $\mu = 4118,33 \text{ €ha}^{-1}$  and  $s = 352,15$  for non-organic production  
653 and  $\mu = 5353,83 \text{ €ha}^{-1}$  and  $s = 457,79$  for organic production (EC, 2013).

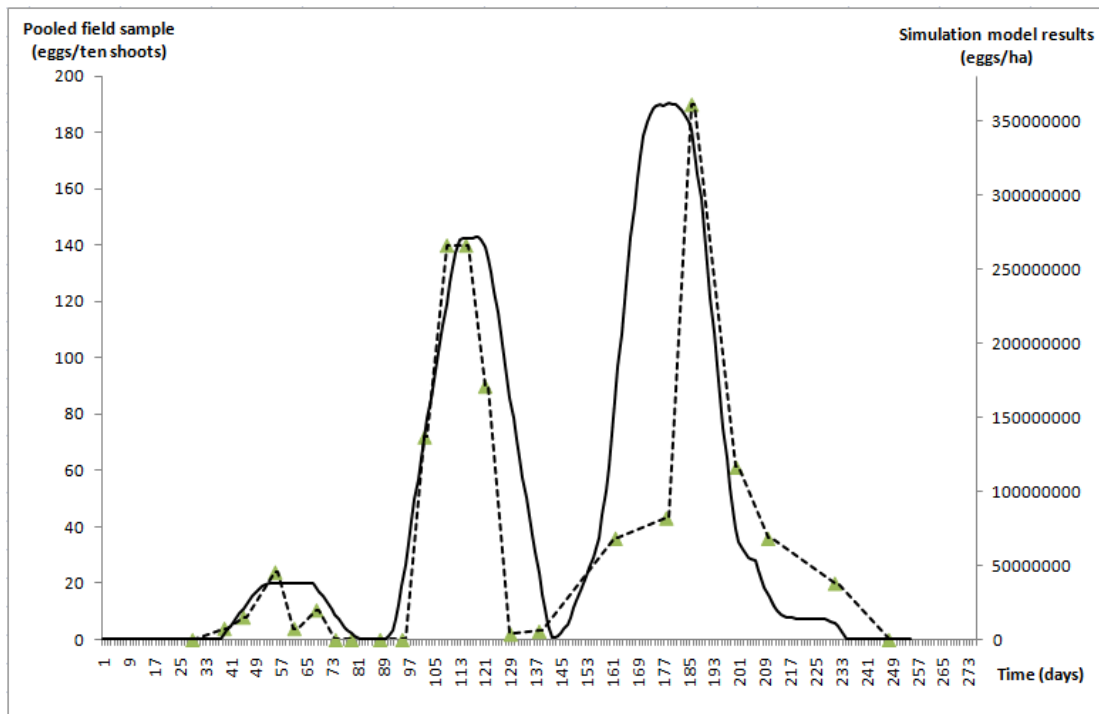
654

<sup>6</sup> Farm Accounting Data Network

<sup>7</sup> With  $\mu$  the average and  $s$  the standard deviation

655 ANNEX D

656 Model calibration for organic production based on field data from 2010, comparing the  
657 pooled field sample (eggs/ten shoots) with the organic model results (eggs ha<sup>-1</sup>).



658

659 Figure D: Model calibration for organic production based on field data from 2010, comparing  
660 the pooled field sample (eggs/ten shoots) with the organic model results (eggs ha<sup>-1</sup>) (-  
661 simulation model, -- field sample data). The units of field measurements (mean eggs/10  
662 shoots) were transformed to yield model parameter units (absolute egg numbers per hectare),  
663 based on 33,84 shoots/tree on average, 5% of the eggs captured and 1714 trees per hectare  
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