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## Modelling land use strategies to optimise crop production and protection of ecologically important weed species

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**Modelling land use strategies to optimise crop production and protection  
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4 **1 Modelling land use strategies to optimise crop production**  
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7 **2 and protection of ecologically important weed species**  
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## 1 **Abstract**

2 There is a need to develop farming systems that enable both a satisfactory level of crop  
3 production and good living conditions for natural species. Wildlife-friendly cropping  
4 techniques, such as a reduced amount of applied herbicide or a lower crop density, might be  
5 adopted in order to maintain populations of weed species of biological interest. An alternative  
6 might be to adopt an intensive cropping system in a part of the field and spare the other part  
7 as set-aside or field margins, available for the development of natural plant species. The  
8 objective of this paper is to present a method to compare two strategies for maintaining a  
9 desirable level of abundance of a given species of interest in agricultural areas, specifically (1)  
10 a strategy based on a wildlife-friendly cropping system in a large cultivated area and (2) a  
11 strategy based on a more intensive cropping system in a reduced area of cultivation. The  
12 principle is to calculate the ratio of crop production obtained with strategy (1) to the  
13 production obtained with strategy (2) for a given target density of natural species. We show  
14 that the value of this ratio, and thus the relative performance of the two strategies, depends on  
15 the density of the weed species that can be maintained in an uncultivated ecological area. The  
16 method is applied in two case studies to compare the relative performance of wildlife-friendly  
17 cropping system and land sparing for maintaining a desirable level of abundance of two plant  
18 species with contrasting ecology and preservation goals.

19  
20 **Keywords:** *Adonis aestivalis*, biodiversity, cropping system, land use, *Poa annua* L.

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## 1 Introduction

2 The intensive use of inputs in crops has caused a decline in biodiversity in European arable  
3 ecosystems (Stoate *et al.*, 2001; van Wenum *et al.*, 2004). Such a decline has been well  
4 documented for birds (Chamberlain *et al.*, 2000), invertebrates, and plants (e.g. Andreasen *et*  
5 *al.*, 1996; Sutcliffe & Kay, 2000 ; Green *et al.*, 2005). Concerns about the impact of intensive  
6 agriculture on ecosystems are arising both among the European population and policy-makers  
7 (Stoate *et al.*, 2001; van Wenum *et al.*, 2004). Gerowitt *et al.* (2003) have recently proposed  
8 that weeds should be considered as ecological goods. Some weed species, e.g. *Poa annua* L.,  
9 are important components of ecosystems because their biomass constitutes a nutrient resource  
10 for birds or other vertebrates (Marshall *et al.*, 2003). Other species, such as *Adonis* species,  
11 have drastically declined in abundance in Western Europe (Aymonin, 1976) and agronomists  
12 are now trying to define precise land use strategies to preserve these species, among others,  
13 from extinction.

14 However, weeds growing in arable land compete with crops for nutrients, light and  
15 water, and are therefore likely to reduce crop yields and the cropping system profitability.  
16 There is a need to develop systems leading to satisfactory levels of crop production and  
17 maintaining appropriate conditions to support populations of natural species. Several  
18 solutions have been proposed such as a reduction of pesticide input (Stoate *et al.*, 2001), the  
19 use of arable field margins (Marshall & Moonen, 2002), or the use of permanent or rotating  
20 set-aside (van Wenum *et al.*, 2004), but little is known about the relative efficiency of these  
21 solutions.

22 Wildlife-friendly cropping techniques, like a reduced amount of applied herbicide (de  
23 Snoo, 1997), a lower crop density and/or restricted fertiliser inputs (Kleijn & van der Voort,  
24 1997) might be adopted in order to maintain populations of weed species of biological interest

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1 (target species). But the adoption of such techniques is likely to induce a yield loss due to the  
2 development of a large weed community. An alternative might be to adopt a land-sparing  
3 strategy of using an intensive cropping system in a part of the field and sparing the other part  
4 as set-aside or field margins, available for the development of natural plant species. Using this  
5 strategy, a high yield would be obtained in the cultivated part of the field, but the absence of  
6 crop on the remaining part results in a loss of production for the farmer. According to Green  
7 *et al.* (2005), the optimal choice between a land-sparing strategy and the use of wildlife-  
8 friendly cropping techniques depends on the density-yield relationship between population  
9 density of a target species growing in a crop and the crop yield. If a small reduction in the  
10 farm inputs is likely to trigger a significant increase in the wildlife while resulting in only a  
11 small reduction in crop production, then the best strategy to optimize the balance between  
12 economy and ecology would be to use all the area for crop production with wildlife-friendly  
13 management. However, if any increase in the wildlife may be obtained only through a strong  
14 reduction in farm inputs, then the best strategy would be to partition the land area with areas  
15 allocated to intensive crop production and areas allocated to wildlife conservation.

16       The impacts of wildlife-friendly techniques and land sparing on crop production and  
17 on weed populations depend on many factors, such as the characteristics of the weed species  
18 growing in the field, the weed densities, and the crop yield values. Choosing the best land use  
19 strategy is not straightforward. In this paper, we present a method to compare two strategies  
20 for maintaining a desirable level of abundance of a given species of interest in the landscape,  
21 specifically (1) a strategy based on a wildlife-friendly cropping system in a large cultivated  
22 area and (2) a strategy based on a more intensive cropping system in a reduced cultivated  
23 area. The proposed method can be used to determine, for each strategy, the area that must  
24 remain uncultivated in order to obtain the targeted density of plants. This method can also be  
25 used to compare the crop production obtained with the two strategies, either for a given

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1 environment or for a series of environments corresponding to different levels of abundance of  
2 the plant species.

3         There is a close relationship between the model of Green *et al.* (2005) and our work.  
4 Both aim at comparing crop production and population densities of target species resulting  
5 from different land use strategies. But the two approaches differ in the method used to  
6 estimate crop production and population densities. Green *et al.* (2005) assessed the relative  
7 performance of the wildlife-friendly and intensive land use strategies using the shape of the  
8 population density-yield function and, more specifically, the convexity or concavity of this  
9 function. Our method is not based on the shape of the density-yield function; the  
10 performances of the two land use strategies are compared from measured or estimated values  
11 of plant densities and crop yields.

12         The value of our approach is illustrated through two case studies, namely (i) *Poa*  
13 *annua*, a common grass weed producing many seeds important in the diet of birds and other  
14 animal species, and (ii) *Adonis* spp. as an example of a rare weed species.

## 16 **Methods**

### 17 **Cultivated area for a target number of plants**

18 Consider an agricultural area with a surface equal to  $S$  and two cropping systems, an intensive  
19 one and a wildlife-friendly one, leading to a density of a plant species of ecological interest  
20 (e.g. *Poa annua*) equal to  $d_I$  and  $d_{WF}$  respectively (plants per unit area). Assume that the  
21 density is equal to  $d_U$  if the field remains uncultivated such as  $d_I < d_{WF} < d_U$ .  $d_U$  is an  
22 indicator of the natural abundance of the species in the environment.

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1 If the intensive cropping system is adopted by the farmer, the number of plants in the field,

2  $Z$ , is related to  $d_I$  and  $d_U$  by

$$3 \quad Z = d_I s_I + (S - s_I) d_U \quad (1)$$

4 where  $s_I$  is the surface of the cultivated area,  $d_I s_I$  is the number of plants obtained in the

5 cultivated part, and  $(S - s_I) d_U$  is the number of plants obtained in the uncultivated part (set-

6 aside or field margins).

7 By dividing the two sides of Eqn (1) by  $S$ , we obtain

$$8 \quad D = d_I f_I + (1 - f_I) d_U \quad (2)$$

9 where  $D$  is the number of plants of ecological interest per unit area at the field level and  $f_I$  is

10 the cultivated area divided by the total field area. As  $0 \leq f_I \leq 1$ , we have  $d_I \leq D \leq d_U$ .

11 We express the fraction of the field that is cultivated ( $f_I$ ) as a function of the number of

12 plants  $D$ . Eqn (2) shows that  $f_I$  is related to  $D$  by

$$13 \quad \begin{aligned} f_I &= 1 && \text{if } D = d_I \\ f_I &= \frac{d_U - D}{d_U - d_I} && \text{if } d_I < D < d_U \\ f_I &= 0 && \text{if } D = d_U \end{aligned} \quad (3)$$

14 A similar equation can be obtained if the wildlife-friendly cropping system is adopted by the

15 farmer:

$$16 \quad \begin{aligned} f_{WF} &= 1 && \text{if } D = d_{WF} \\ f_{WF} &= \frac{d_U - D}{d_U - d_{WF}} && \text{if } d_{WF} < D < d_U \\ f_{WF} &= 0 && \text{if } D = d_U \end{aligned} \quad (4)$$



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1 where  $f_{WF}$  is the cultivated area divided by the total area when the wildlife-friendly cropping  
 2 system is adopted. As  $d_{WF} \geq d_I$ , we have  $f_{WF} \geq f_I$ .

3 The two functions defined by Eqs (3) and (4) can be used to compute the area that can  
 4 be cultivated by the farmer as a function of a target value  $D$  of number of plants per unit area.  
 5 These two functions are graphically compared in Figure 1. The wildlife-friendly cropping  
 6 system allows the farmer to cultivate a larger fraction of his field for a given target value  $D$ .  
 7 The drawback of this cropping system is that it may lead to a lower total yield than an  
 8 intensive cropping system. It is thus necessary to compare the crop production and/or the  
 9 income obtained with two cropping systems to make the final choice.

### 10 Crop production assessment

11 Let  $y_I$  and  $y_{WF}$  denote the yield values obtained in the cultivated part with the intensive and  
 12 wildlife-friendly cropping systems respectively. The crop production per unit area obtained  
 13 with the two strategies for a given target number of plants  $D$  are noted  $P_I$  and  $P_{WF}$ , and are  
 14 expressed as:

$$15 \quad P_I = y_I \times f_I = y_I \frac{d_U - D}{d_U - d_I} \quad (5)$$

$$16 \quad P_{WF} = y_{WF} \times f_{WF} = y_{WF} \frac{d_U - D}{d_U - d_{WF}} \quad (6)$$

17 Eqs (5) and (6) can be used to compute the crop production obtained with the two  
 18 strategies. Also, these equations show that the ratio  $\frac{P_{WF}}{P_I}$  is defined by

$$19 \quad R = \frac{P_{WF}}{P_I} = \frac{y_{WF} \times [d_U - d_I]}{y_I \times [d_U - d_{WF}]} \quad (7)$$

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1           The ratio (7) depends on the yields and plant densities obtained with the two cropping  
2 systems, and on the plant density obtained in the uncultivated part of the field, but does not  
3 depend on the target value  $D$ .

4           The partial derivatives of  $R$  were computed in order to study the sensitivity of  $R$  to  
5 crop yields and weed densities. The signs of the derivatives show that  $R$  increases as a  
6 function of  $y_{WF}$  and  $d_{WF}$ , but decreases as a function of  $y_I$ ,  $d_I$ , and  $d_U$  (Table 1).

7           The crop production ratio  $R$  can be used in two ways. Firstly, it is possible to compute  
8 a single  $R$  value for a given environment, characterised by a given value of  $d_U$ . This approach  
9 is useful in order to compare the crop production obtained with two cropping systems in a  
10 specific environment. Secondly, it is possible to compute  $R$  for a series of environments  
11 characterised by different values of  $d_U$ . This second approach allows one to study the  
12 sensitivity of  $R$  to the natural abundance of the plant species. It is interesting to calculate the  
13 threshold value of  $d_U$  corresponding to  $R=1$ . According to Eqn (7), this value is

$$14 \quad d_{uT} = \frac{y_I \times d_{WF} - y_{WF} \times d_I}{y_I - y_{WF}} \quad (8)$$

15           When  $d_U$  is equal to  $d_{uT}$ , the production obtained with the two cropping systems is  
16 the same. When  $d_U$  is higher than  $d_{uT}$ , the crop production is higher with the intensive  
17 cropping system than with the wildlife-friendly cropping system.

18           In some applications, it may be useful to replace  $y_I$  and  $y_{WF}$  in Eqs (7) and (8) by the  
19 corresponding gross margins associated with the two cropping systems. This is useful when  
20 the prices and the costs associated with the two cropping systems must be taken into account.

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## 1 **Estimation**

2 The calculation of  $f_I$  and  $f_{WF}$  requires a knowledge of the plant densities  $d_I$ ,  $d_{WF}$ , and  $d_U$ .  
3 In addition, the calculation of  $R$  requires a knowledge of the yield values  $y_I$  and  $y_{WF}$ . These  
4 can be estimated from yield and plant density measurements performed in cropping system  
5 experiments. The experiments must include treatments corresponding to different cropping  
6 systems. Yield and natural plant species density must be recorded for each treatment. It is also  
7 useful to have a 'set-aside' treatment in the same field, in which the plant density is  
8 recorded. If this treatment is present it is possible to estimate  $d_U$ . If not, it is possible to  
9 compute  $f_I$ ,  $f_{WF}$ , and  $R$  for different  $d_U$  taken within a reasonable range of values as shown  
10 below.

## 12 **Case studies**

13 Two case studies are presented here for two species with contrasting ecology and preservation  
14 goals. The first example is of an *Adonis* species with very low abundance, at risk of  
15 population extinction. In this case the main objective is to preserve low densities of the  
16 species to avoid its complete disappearance, but fortunately the target densities are low  
17 enough to avoid any crop yield loss. The second example regards a common species (*Poa*  
18 *annua*), which is controlled at very low densities in intensive cropping systems, while it is  
19 recognised for its ecological function if significant population densities are maintained.

## 20 **Maintaining the population of an *Adonis* species**

21 The populations of *Adonis* species have steadily decreased in Western Europe for several  
22 decades. Fifty years ago three species of *Adonis* (*A. aestivalis*, *A. flammea*, *A. annua*) were  
23 still common in wheat fields in France. These species became endangered (less than 1 plant

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1 km<sup>-2</sup>) in the 1970s (Aymonin, 1976) and are no longer found in intensive crops. In this case study, we compare two land use strategies for increasing the population of this species in a given arable area cropped with winter wheat. The first strategy consists in using an intensive cropping system characterised by  $y_I=8$  t ha<sup>-1</sup> and  $d_I=0$ . These values are commonly observed in France when the crop is cultivated using conventional practices. The second strategy consists in using a wildlife-friendly cropping system characterised by  $y_{WF}=6$  t ha<sup>-1</sup> and by a plant density  $d_{WF}$  in the range 0.005-0.01 plants m<sup>-2</sup>. These values may be obtained in winter wheat fields with low herbicide use, low sowing densities, late sowing dates associated with a stale seed bed, and low fertiliser inputs. However, the density increase of such a rare species induced by wildlife-friendly practices is highly unpredictable. In Sweden, Rydberg & Milberg (2000) found rare weed species in organic arable fields, but on a smaller scale in a cropping system experiment in Germany, none of the species recorded on fields with organic systems were considered rare (Gruber *et al.*, 2000). According to Squire *et al.* (2000), the reduction in herbicide use can result in an increase in the number of weed species, but the commonest species are likely to increase the most, while rarer species are less favoured.

The proportion of the area cultivated ( $f$ ) and the crop production ( $P$ ) depend on  $D$  (Eqs 3-6) and this dependence is illustrated in Figures 2 (a, b) and 3 (a, b) where two values are considered for  $D$ , 0.006 and 0.009 plants m<sup>-2</sup>. The higher the value of  $D$ , the lower is the cultivated area and crop production. The cultivated area is always larger with the wildlife-friendly cropping system than with the intensive cropping system (Figure 2 a, b).

Figures 2 (a, b) and 3 (a, b) show that the cultivated area and the crop production depend highly on the plant density in the uncultivated land. When the density  $d_U$  is low, the cultivated area (and therefore crop production) must be significantly reduced to reach the

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1 target number of plants  $D$ . For example, when  $d_U=0.01$  plants  $m^{-2}$ , it is necessary to keep  
 2 more than 80% of the area uncultivated to reach the target number of plants  $D=0.009$  plants  
 3  $m^{-2}$  (Figure 2b).

4 The values of  $d_{uT}$  and  $R$  do not depend on the target number of plants  $D$  (Eqs 7 and  
 5 8). If we assume  $d_I=0$ ,  $y_{WF}=6$  t  $ha^{-1}$ , and  $y_I=8$  t  $ha^{-1}$ , the plant density threshold  $d_{uT}$  is equal  
 6 to  $4 \times d_{WF}$  (Eqn 8). For example, if the plant density obtained with the wildlife-friendly  
 7 cropping system is equal to  $0.005$  plants  $m^{-2}$ , the threshold value is equal to  $d_{uT}=0.02$  plants  
 8  $m^{-2}$ . In this case, the highest winter wheat production is obtained with the intensive cropping  
 9 system if the plant density in the uncultivated part of the field ( $d_U$ ) is above  $0.02$  plants  $m^{-2}$ .  
 10 Alternatively, if the plant density in the uncultivated part of the field is below  $0.02$  plants  $m^{-2}$ ,  
 11 the highest crop production is obtained with the wildlife-friendly cropping system. This is  
 12 illustrated in Figure 4a where the values of the crop production ratio  $R$  (Eqn 7) are reported  
 13 for a series of values of  $d_U$ . The value of  $R$  is more than 1 when the density  $d_U$  is less than  
 14  $0.02$  plants  $m^{-2}$ . This threshold value seems rather low. But the densities of *Adonis* spp.  
 15 observed in set-aside in France are generally less than  $0.02$  plants  $m^{-2}$  (Chauvel, personal  
 16 communication). Thus, the strategy based on the wildlife-friendly cropping system will give  
 17 the highest crop production in most of the environments.

18 The derivatives presented in Table 1 were used to study the sensitivity of  $R$  to crop  
 19 yield and plant densities. The derivative values were computed for  $d_U=0.02$  plants  $m^{-2}$ , and  
 20  $d_{WF}=0.005$  or  $d_{WF}=0.01$  plants  $m^{-2}$ . The results show that  $R$  is much more sensitive to the  
 21 plant densities  $d_I$ ,  $d_{WF}$ , and  $d_U$  than to the crop yield values  $y_{WF}$  and  $y_I$  (Table 2). For  
 22 example, when  $d_{WF}=0.005$ ,  $\frac{\partial R}{\partial d_{WF}}$  is equal to 66.67 but  $\frac{\partial R}{\partial y_{WF}}$  is only equal to 0.17. This is

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1 due to the low density values of the *Adonis* spp. in both cultivated and uncultivated areas. A  
 2 small increase in  $d_{WF}$  leads to a much larger cultivated area and crop production being  
 3 obtained with the wildlife-friendly cropping system and thus to a much higher value of  $R$ .  
 4 Table 2 also shows that  $R$  is very sensitive to  $d_U$ , especially when  $d_{WF}=0.01$ . A small  
 5 increase of  $d_U$  leads to a much lower value of  $R$ . This result is consistent with the response  
 6 curves shown in Figure 4.

### 7 **Maintaining the population of *Poa annua***

8 *Poa annua* is a grass weed species with a short life cycle and an extended period of  
 9 emergence in crops, so this species may provide a regular supply of seeds to feed birds and  
 10 other vertebrates without competing strongly with the infested crop. In addition, the  
 11 populations of *Poa annua* host a large number of insect species. It is therefore an important  
 12 component of the ecosystem (Marshall *et al.*, 2003). In this case study, we compare two land  
 13 use strategies for increasing the population of this weed species in a winter wheat crop. The  
 14 first strategy consists of using an intensive cropping system characterised by  $y_I=8 \text{ t ha}^{-1}$  and  
 15  $d_I=0$  because of the systematic use of herbicides efficient against this species. The second  
 16 strategy is to use a wildlife-friendly cropping system characterised by  $y_{WF}=6 \text{ t ha}^{-1}$  and by a  
 17 plant density  $d_{WF}$  in the range 20-80 plants  $\text{m}^{-2}$ . These values may be observed in winter  
 18 wheat fields in diversified crop rotations with Integrated Weed Management, avoiding among  
 19 other things the use of urea herbicides, and in organic farming (Mortensen *et al.*, 2000).

20 The cultivated area and the crop production values (Eqs 3-6) are shown in Figures 2  
 21 (c, d) and 3 (c, d) for  $d_{WF}=20$  and for two values of  $D$ , 50 and 80 plants  $\text{m}^{-2}$ . These target  
 22 density values are high enough to ensure a good accessibility of the weed resources to other  
 23 trophic groups (birds, carabids etc.). Here also, the cultivated area is invariably larger with the

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1 wildlife-friendly cropping system than with the intensive cropping system (Figure 2). Figure 3  
 2 (c, d) shows that the crop production obtained with the intensive cropping system is higher  
 3 than that obtained with the wildlife-friendly cropping system for all the tested values of  $d_U$   
 4 when  $d_{WF}=20$ . Figures 2 (c, d) and 3 (c, d) also show that when the density  $d_U$  is low, it is  
 5 necessary to greatly reduce the cultivated area (and hence the crop production) to reach the  
 6 target number of plants  $D$ . For example, when  $d_{WF}=20$  and  $d_U=100$  plants  $m^{-2}$ , almost all the  
 7 land must be kept uncultivated to reach the target number of plants  $D=80$  plants  $m^{-2}$  (Figure  
 8 3d).

9 Here also, the plant density threshold  $d_{uT}$  (Eqn 8) is equal to  $4 \times d_{WF}$ . For example, if  
 10 the plant density obtained with the wildlife-friendly cropping system is 20 plants  $m^{-2}$ , the  
 11 threshold value is  $d_{uT}=80$  plants  $m^{-2}$ . In this case, the highest winter wheat production is  
 12 obtained with the intensive cropping system if the plant density in the uncultivated part of the  
 13 field ( $d_U$ ) is higher than 80 plants  $m^{-2}$ .

14 Figure 4 (c, d) shows the values of the crop production ratio  $R$  (Eqn 7) for a series of  
 15 values of  $d_U$  (100-400 plant. $m^{-2}$ ) and for two contrasting values of  $d_{WF}$ , 20 and 80 plants  $m^{-2}$ .  
 16 When  $d_{WF}=20$ , the value of  $R$  is lower than 1 for all the tested values of  $d_U$  (Figure 4c). This  
 17 is because, in this case,  $d_{uT}=80$  plants  $m^{-2}$  and all the tested values of  $d_U$  are above this  
 18 threshold. Conversely, when  $d_{WF}=80$ ,  $R$  is more than 1 for most of the tested values of  $d_U$   
 19 (Figure 4d).  $R$  values of less than 1 are obtained only when  $d_U$  exceeds 320 plants  $m^{-2}$ .

20 The derivatives of  $R$  were computed for  $d_U=200$  plants  $m^{-2}$  and  $d_{WF}=20$  or  $d_{WF}=80$   
 21 plants  $m^{-2}$  (Table 2). The results show that  $R$  is less sensitive to the plant densities  $d_I$ ,  $d_{WF}$ ,  
 22 and  $d_U$  than to the crop yield values  $y_{WF}$  and  $y_I$ . This is because the plant densities  $d_{WF}$  and

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1  $d_U$  are high and because the difference between these densities is large. A small increase or  
2 decrease in plant density does not significantly affect the crop production ratio.

## 4 Discussion

5 The theoretical analysis of two strategies of management of agricultural areas presented in  
6 this paper is an attempt to study the trade-off between wildlife conservation and crop  
7 production, adapted to the particular case of plant species referred to as 'weeds', because their  
8 typical environment is cultivated fields and their surroundings. Green *et al.* (2005) considered  
9 a similar problem at the regional level, comparing two options, namely (a) wildlife-friendly  
10 farming on the whole area and (b) land sparing, with a proportion of land devoted to wildlife  
11 conservation and the remainder devoted to crop production. These authors showed that the  
12 optimal choice between these options depends on the shape of the relationship between  
13 wildlife density and crop production. In our approach, the best land use strategy is not  
14 determined from the shape of yield-density relationship but from values of crop yield and  
15 weed densities. The validity of our model and of the numerical results is discussed below.

### 16 Estimation of the model parameters

17 Crop yields and weed densities can be estimated from experiments or farmers' field surveys.  
18 Due to the widespread use of herbicides, weed densities are often very low, for most species.  
19 Indeed, only a few species, which are not very sensitive to the herbicides, can develop dense  
20 populations (e.g. Colbach *et al.*, 2000). *Adonis* species have almost completely disappeared  
21 from areas with intensive agriculture (Pichot, 1991), either because they are sensitive to  
22 herbicide or because populations of these species need particular environmental conditions to  
23 grow (e.g light availability throughout the plant life cycle) that are not met in current intensive



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1 dense crop canopies boosted by high nitrogen fertiliser inputs (Kleijn & van der Voort, 1997).  
2 In contrast, *Poa annua* is a very widespread species that was found in 11 to 100% of the fields  
3 in different European regions on a North-South transect from Sweden to Italy (Radics *et al.*,  
4 2000), and ranked the second most frequently occurring weed species for the frequency of  
5 presence in a large field survey conducted in winter cereals in the UK in 1988 (Whitehead &  
6 Wright, 1989). However, it is well controlled by herbicide programmes in wheat crops in  
7 most regions with intensive cropping systems. It is therefore reasonable to choose a density of  
8 zero for both species in intensive cropping systems in the simulation analysis.

9 The density of weeds of ecological interest in more wildlife-friendly cropping systems  
10 may be derived either from old surveys of weed flora performed before the increase in  
11 herbicide and nitrogen use, from recent surveys of organic farming (Hyvönen *et al.*, 2003;  
12 Rydberg & Milberg, 2000), or from long-term experiments aimed at testing the feasibility of  
13 cropping systems based on the principles of Integrated Pest Management. However, there  
14 may be large differences in plant density for a given species between different fields, from  
15 different soil and climatic conditions and conducted with different “low-input” cropping  
16 systems (e.g. Marshall & Arnold, 1994), so the plant density to be expected in a wildlife-  
17 friendly cropping system is highly unpredictable.

18 In uncultivated areas, even less information is available regarding the density of  
19 “weed” species although, as shown in this paper, the choice of the strategy that supports best  
20 biological diversity depends on this information.

21 Crop yield and weed values are always variable and imperfectly estimated. It is thus  
22 necessary to deal with this uncertainty using, for example, the expression of the derivatives of  
23  $R$  given in this paper. In all cases, we advise to perform a sensitivity analyse of the ratio  $R$  to  
24 crop yield and weed density values. Note that, in some practical applications, it may be useful

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1 to use gross margins instead of crop yields in order to account for fertiliser and pesticide  
2 prices.

### 3 **Validity of the model equations**

4 The equations presented in this paper are based on the hypothesis that the density of weed  
5 species would be higher in uncultivated areas than in low-input cropping systems. This  
6 hypothesis is debatable: indeed some weed species grow preferentially in cultivated fields,  
7 where they can find an environment favourable to their life history (for example: short life  
8 cycle, seed dormancy, seed persistence in the soil, seasonal emergence, high level of seed  
9 production).

10 It has never been demonstrated that *Adonis* species would develop stable populations  
11 in uncultivated areas. In long-term set-aside, the overall soil seed bank is likely to increase  
12 dramatically if various annual species produce seeds. However, the growing environment  
13 would become strongly competitive after a few years, which is probably not favourable for  
14 *Adonis* spp.. If annual species are not allowed to produce seeds, for example through repeated  
15 mowing, then the proportion of perennials is likely to change more rapidly, which would also  
16 provide a very competitive environment for young *Adonis* seedlings. *Poa annua* is a very  
17 short-stemmed species, which would also have difficulty developing stable populations in  
18 long term set-aside with a dense competitive canopy.

19 Short-term set-aside, rotating each year in the landscape, are likely to provide more  
20 open canopies that would be much more favourable for weakly competitive species such as  
21 *Adonis* spp. and *P. annua*. However, in rotational set-aside, the presence of a species is  
22 strongly related to the presence of a significant number of seeds in the seed bank, and this is  
23 unlikely for a species that has been very rarely observed in a given landscape for many years,  
24 such as *Adonis* spp..

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## 1 **Relative performance of the land use strategies**

2 The first case study presented above showed that, for the *Adonis* spp., the value of the crop  
3 production ratio  $R$  (Eqn 7) is highly sensitive to density in the wildlife-friendly cropping  
4 system ( $d_{WF}$ ) and to the density in uncultivated areas ( $d_U$ ). If  $d_{WF}$  is set at 0.005 plants  $m^{-2}$   
5 (Figure 4a), the ratio  $R$  shifts from highly favourable to the wildlife-friendly cropping system  
6 when  $d_U = 0.01$  plants  $m^{-2}$  to more favourable to the intensive system when  $d_U = 0.04$  plants  
7  $m^{-2}$ . The fourfold increase in weed density is not dramatic compared with the wide range of  
8 densities observed in cultivated fields. If the *Adonis* spp. density is low both in cultivated  
9 areas with low inputs and in uncultivated areas, then the objective of maintaining a significant  
10 population in the landscape will be reached only with a severe decline in the proportion of the  
11 area cultivated (Figure 2b), and therefore a proportional decline in the crop production, which  
12 is likely to be unacceptable for social reasons.

13 For *P. annua*, the ratio  $R$  is less sensitive to plant density, but the conclusions are  
14 different depending on whether a high or a low value is assumed for  $d_{WF}$ . If  $d_{WF}$  is about 20  
15 plants  $m^{-2}$ , the land-sparing option with intensive cropping is more favourable for all the  
16 explored values of density in uncultivated areas. However, if the density  $d_{WF}$  is about 80  
17 plants  $m^{-2}$ , which is only four times higher, then the wildlife-friendly cropping system is more  
18 profitable for most of the explored values of density in uncultivated areas.

19 The results of the calculations should be considered with caution because of the  
20 uncertainty regarding the contribution of target species in uncultivated areas. However, we  
21 can still make an attempt to identify some trends for land use recommendation as far as weed  
22 species conservation is concerned. For rare species such as *Adonis* spp., it is likely that plant  
23 density in uncultivated areas devoted to wildlife conservation would be only slightly higher  
24 than in low-input wildlife-friendly cropping systems. This corresponds to the left-hand part of  
25 Figures 4a and 4b, where the ratio  $R$  indicates higher overall crop production with the low-

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1 input wildlife-friendly cropping system. For common species with low competitive ability  
2 such as *P. annua*, a density of 80 plants m<sup>-2</sup> seems likely to be reached and maintained in a  
3 low-input cropping system, and the density in uncultivated areas would be only slightly  
4 higher. These hypotheses correspond to the left-hand part of the Figure 4d, which is again  
5 more favourable to the low-input wildlife-friendly cropping system.

## 7 **Conclusion**

8 The model presented in this paper can be used to compare the relative performance of  
9 wildlife-friendly cropping system and land sparing for maintaining a desirable level of  
10 abundance of a given species of interest in agricultural areas. We showed that the relative  
11 performance of the two strategies depends on the plant densities in cultivated fields and  
12 uncultivated areas, but does not depend on the desired level of abundance of the species of  
13 interest. This result emphasises the need for more comprehensive knowledge about the effects  
14 of management options on weed species of ecological value in both uncultivated areas and  
15 low-input cropping systems.

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1 Table 1. Expressions and signs of the derivatives of  $R = \frac{y_{WF} \times (d_U - d_I)}{y_I \times (d_U - d_{WF})}$ . It is assumed that

2  $d_U > d_{WF} > d_I$ .

3

Derivative	Sign
$\frac{\partial R}{\partial y_{WF}} = \frac{d_U - d_I}{y_I \times (d_U - d_{WF})}$	+
$\frac{\partial R}{\partial y_I} = \frac{-y_{WF} \times (d_U - d_I)}{y_I^2 \times (d_U - d_{WF})}$	-
$\frac{\partial R}{\partial d_{WF}} = \frac{y_{WF} \times (d_U - d_I)}{y_I \times (d_U - d_{WF})^2}$	+
$\frac{\partial R}{\partial d_I} = \frac{-y_{WF}}{y_I \times (d_U - d_{WF})}$	-
$\frac{\partial R}{\partial d_U} = \frac{y_{WF} \times (d_I - d_{WF})}{y_I \times (d_U - d_{WF})^2}$	-

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7 2 Table 2. Values of the derivatives of  $R$  for  $y_I=8 \text{ t.ha}^{-1}$ ,  $y_{WF}=6 \text{ t.ha}^{-1}$ ,  $d_I=0$ , and for low and high  
8  
9 3 densities  $d_{WF}$  of *Adonis sp.* and *Poa annua*.  
10  
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12 4

$d_{WF}$ (plants $\text{m}^{-2}$ )	$d_U$ (plants $\text{m}^{-2}$ )	$R$	Values of the derivatives of $R$				
			$\frac{\partial R}{\partial y_{WF}}$	$\frac{\partial R}{\partial y_I}$	$\frac{\partial R}{\partial d_{WF}}$	$\frac{\partial R}{\partial d_I}$	$\frac{\partial R}{\partial d_U}$
<i>Adonis sp.</i>							
0.005	0.02	1	0.17	-0.125	66.67	-50	-16.17
0.01	0.02	1.5	0.25	-0.19	150	-75	-75
<i>Poa annua</i>							
20	200	0.83	0.14	-0.104	0.004	-0.0042	-0.00046
80	200	1.25	0.21	-0.156	0.01	-0.0063	-0.0042

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## Figure captions

Figure 1. Relationship between the target number of plants per unit area ( $D$ ) and the fraction of the field area that can be cultivated ( $f$ ) with an intensive cropping system (continuous line) and with a wildlife-friendly cropping system (dashed line).

Figure 2. Ratio of the cultivated area to the total area obtained with the wildlife-friendly cropping system (bold line) and with the intensive cropping system (thin line) for *Adonis* (a, b) and *Poa annua* (c, d). For *Adonis*, the calculations were performed with  $d_{WF}=0.005$  plants  $m^{-2}$ , and  $D=0.006$  plants  $m^{-2}$  (a) or  $D=0.009$  plants  $m^{-2}$  (b), and the value of  $d_U$  was in the range 0.01-0.1 plants  $m^{-2}$ . For *Poa annua*, the calculations were performed with  $d_{WF}=20$  plants  $m^{-2}$ , and  $D=50$  plants  $m^{-2}$  (c) or  $D=80$  plants  $m^{-2}$  (d), and the value of  $d_U$  was in the range 100-400 plants  $m^{-2}$ .

Figure 3. Crop production obtained with the wildlife-friendly cropping system (bold line) and with the intensive cropping system (thin line) for *Adonis* (a, b) and *Poa annua* (c, d). For *Adonis*, the calculations were performed with  $d_{WF}=0.005$  plants  $m^{-2}$ , and  $D=0.006$  plants  $m^{-2}$  (a) or  $D=0.009$  plants  $m^{-2}$  (b), and the value of  $d_U$  was in the range 0.01-0.1 plants  $m^{-2}$ . For *Poa annua*, the calculations were performed with  $d_{WF}=20$  plants  $m^{-2}$ , and  $D=50$  plants  $m^{-2}$  (c) or  $D=80$  plants  $m^{-2}$  (d), and the value of  $d_U$  was in the range 100-400 plants  $m^{-2}$ .

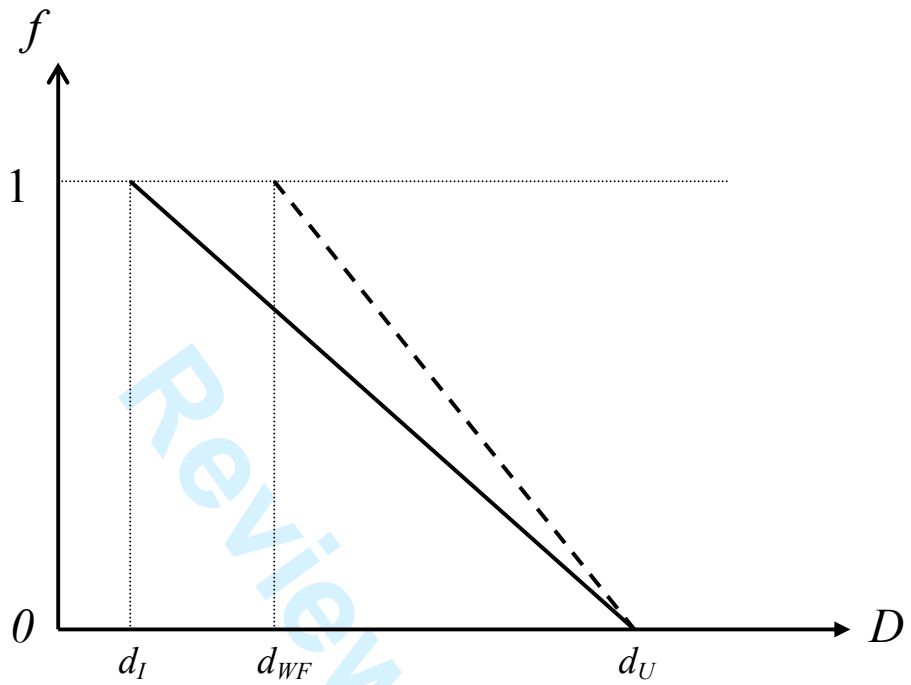
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1  
2  
3 1 Figure 4. Ratio ( $R$ ) of the crop production obtained with the wildlife-friendly cropping system  
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5 2 to the crop production obtained with the intensive cropping system for *Adonis* (a, b) and *Poa*  
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7 3 *annua* (c, d). For *Adonis*, the calculations were performed with  $d_{WF}=0.005$  plants  $m^{-2}$  (a) and  
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9 4  $d_{WF}=0.01$  plants  $m^{-2}$  (b), and the value of  $d_U$  was in the range 0.01-0.1 plants  $m^{-2}$ . For *Poa*  
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11 5 *annua*, the calculations were performed with  $d_{WF}=20$  plants  $m^{-2}$  (c) and  $d_{WF}=80$  plants  $m^{-2}$   
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13 6 (d), and the value of  $d_U$  was in the range 100-400 plants  $m^{-2}$ .  
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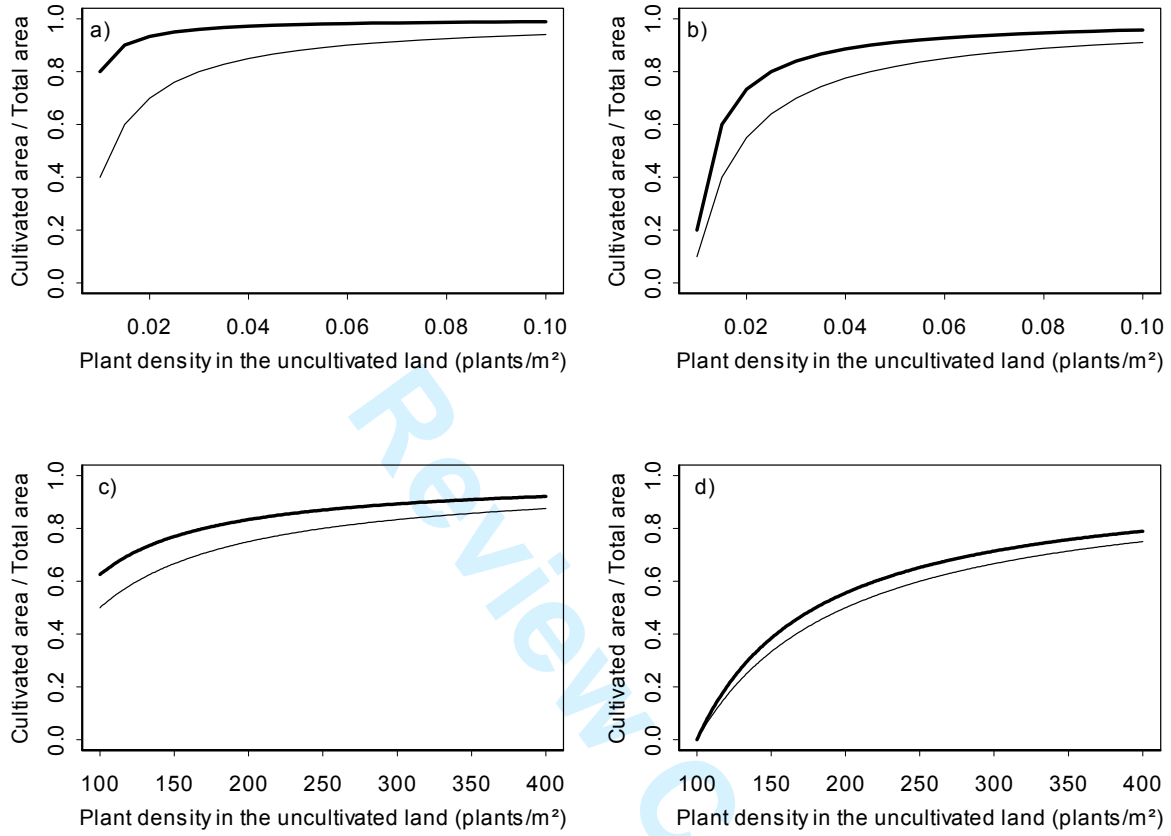
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1 Figure 2

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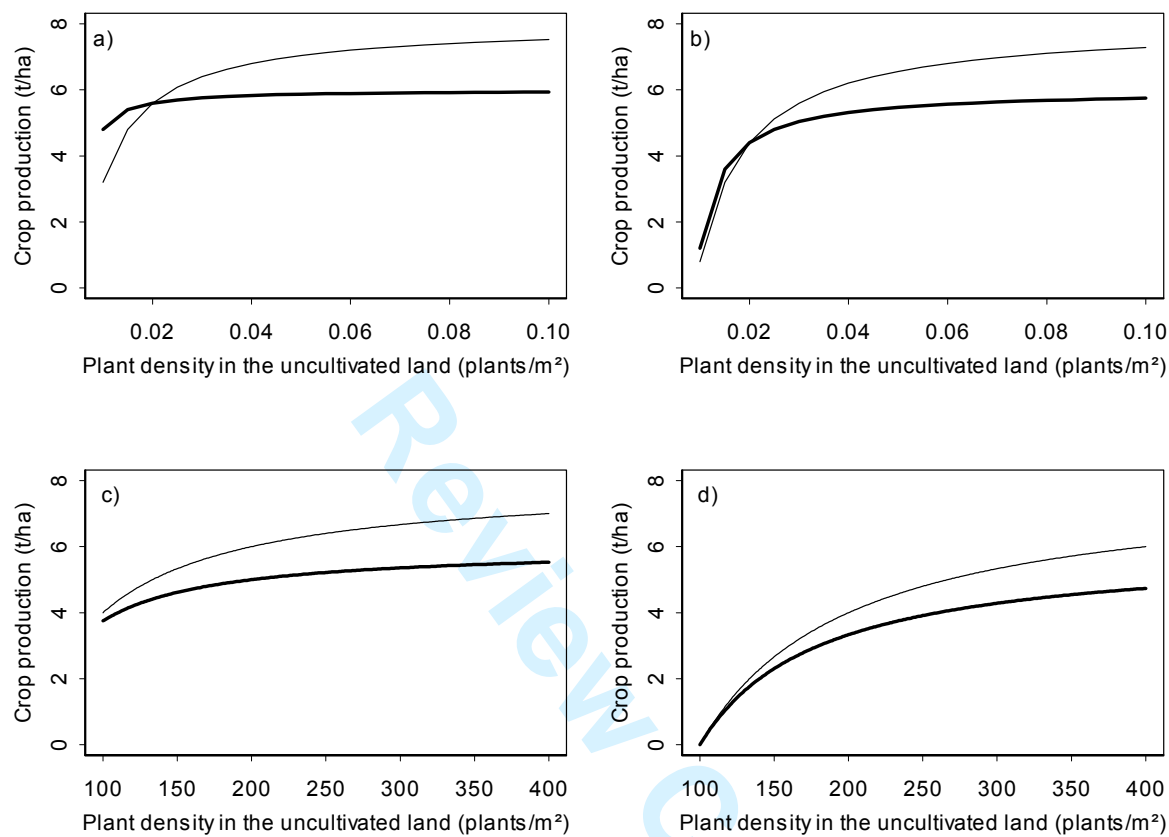


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1 Figure 3

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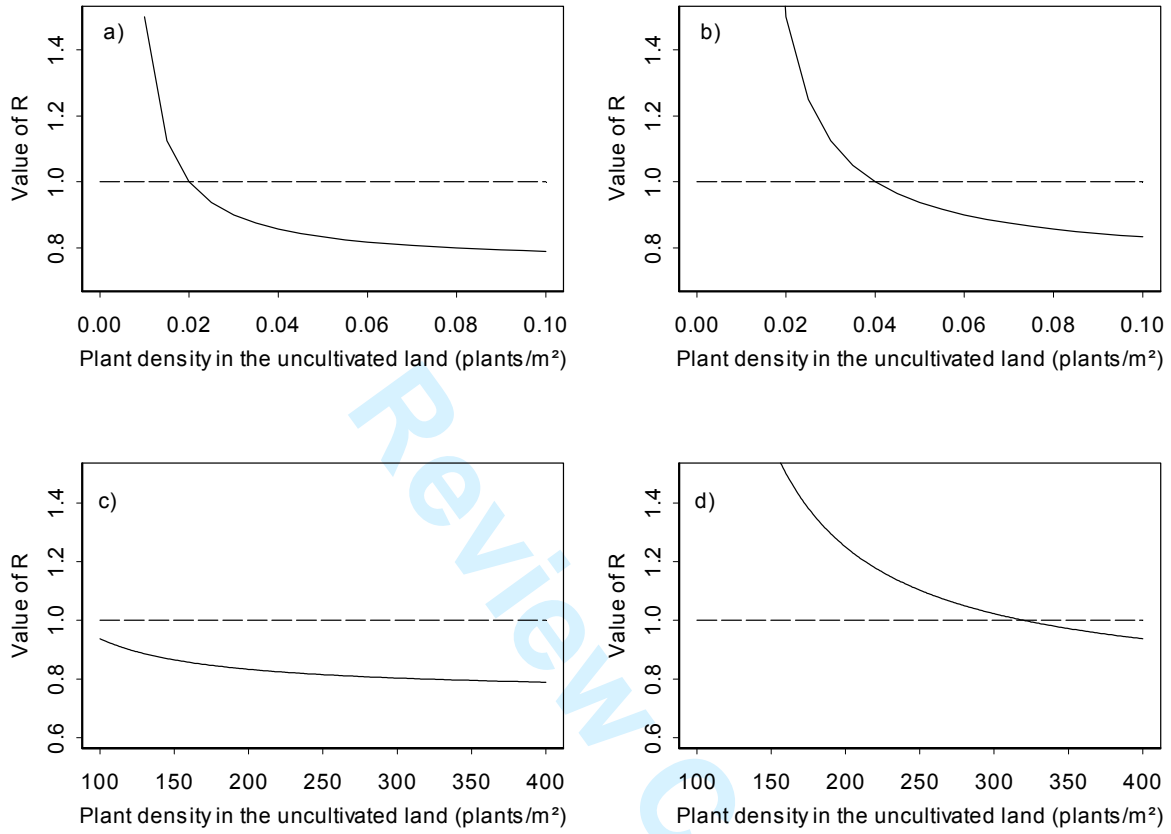
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1 Figure 4

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