# Optimal Management of Mixed Landscape of Forests and Croplands for Pollination Services using Mixed Integer Non-Linear Programming

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## ABSTRACT

The world's forests are rapidly being cleared for for agricultural development. However, poorly managed land conversion decreases the potential ecosystem services provided by remaining natural areas. Specifically, in this study the loss of pollination services provided by native pollinators. I determined the optimal arrangement of forest and cropland so as to provide maximum pollination services in the landscape. I quantified the pollination services based on the distance between the forest area and cropland area in the landscape. Compactness constraints limit the area to perimeter ratio of each land type, cropland and forest. I used MINLP to find the optimal land-use configuration. Using this model, I explored different pollinator types and crop types to determine the combination producing the highest pollination services. Sensitivity analysis of these parameters revealed that shorter-flying pollinators may be better pollinator for a particular crop than stronger-fliers. Overall, my optimization model provides a blueprint of how to optimally design forest conversion to make agriculture more sustainable by ensuring the pollination services provided from the forests remain.

## KEYWORDS

agroforestry, optimal land reserve, forest fragmentation, quantifying ecosystem services,
Mixed Integer Non-Linear Programming (MINLP)

# INTRODUCTION

Recent large scale land-use change has rapidly degraded ecosystem services, defined as the benefits provided by ecological products and processes (Daily et al. 1990). For example, forests provide mitigation of climate change, shelters for a number of animals, and pest control for agriculture (Chazdon 2008). Fresh air and clean water are regenerated through healthy ecosystems (Salzman 2005). However, these values of ecosystems are often ignored in economic markets despite their significant influence on human livelihoods and economies. Costanza et al (1997) estimated the total value of ecosystem services on earth at 33 billion US dollar per year. Many of the values are at the risk of disappearing due to the human development of nature.

One of the biggest negative impacts on ecosystem services is tropical deforestation for agricultural and urban development. Based on the International Bank for Reconstruction and Development data, Areas of tropical forest as large as 80% of Great Britain have been lost to deforestation each year since 1990. As a result, the area of tropical forests will be reduced from 18.4 million km$^2$ in 1990 to 9.7 million km$^2$ by 2025 (Stern et al. 1996). Ultimately, the ecosystem services produced by these forests such as pest controls and pollination services will likely be lost, and the consequent economic and social loss would be enormous (Easterling and Apps 2005). Losses will be shared not only by local people, but also by the global economy.

Deforestation reduces the world potential crop yield because forests provide the main habitats for native pollinators required by agriculture. Although most tropical development seeks to increase agricultural yield, deforestation often limits the maximum yield per area by poorly managed land conversion (McDonald et al. 2002). Conservation of natural habitat for pollinators is essential for efficient crop production because modern agriculture strongly depends on animals for pollination (Klein et al. 2007, Gallai et al. 2009). Optimal reserve site selection based on the economic value of ecosystem services is one approach to emerging green economies (Williams et al. 2005).Better spatial arrangement of croplands within forests can contribute to sustainable development and agricultural practices by balancing conservation and crop production.

In this study, I model forest conversion to cropland to maximize crop yield through pollination services by selecting the arrangement of landscape units to be developed in the given region of forests. I quantify pollination services provided from the forest near the developed new croplands using mathematical functions based on accumulated ecological data and optimize the landscape using the methods of operations research. I predict that the integration of the two different field of science would produce more policy-oriented outcomes. The results contribute to sustainable forest development practices in developing countries.

## METHODS

### Production function

To quantify the pollination services in terms of crop yield, I constructed mathematical functions of crop yield relating the number of pollinating visitors [$V_{ij}$] and the distances from croplands to forests [$D_{ij}$]. The model uses parameters spanning an empirically feasible range for the crop species and pollinator species. I estimated the following values from the literature: (1) carrying capacity of the forest for the pollinators [$Kp$], (2) distance that pollinators can fly [$d$], (3) maximum crop density [$Kc$], and (4) likelihood of pollination of the crop by visiting pollinators [$r$]. Parameter descriptions I used for this model are summarized in Box 1.

The first function (eq1) estimates the relationship between the distance to the cropland in meters [$D_{ij}$] and the number of pollinators that can visit the cropland [$V_{ij}$]. With increasing distance from cropland $i$ to habitat $j$, the number of pollinators that can visit the cropland exponentially decreases as a result of the physical limitation of flying of the pollinators (Carvalheiro et al. 2010). The function is expressed as

$$V_{ij} = Kp * e^{-d*D_{ij}} \quad \text{(eq1)}$$

where $d$ is the particular parameter for the pollinator type indicating the inverse of the physical ability to fly and $D_{ij}$ is the distance from the forest $j$ to the cropland $i$. For each set of cropland $i$ and forest $j$, I calculated the value of the number of pollinators. $V_{ij}$ represents the number of the pollinators travelling from forest $j$ to cropland $i$.

To estimate the total number of pollinators for each crop cell, I calculated the sum of the first function with respect to $j$ (eq 2). $TV_i$ represents the number of total visitors to cropland $i$ from all forests in the region, calculated as follows:

$$TV_i = \sum_{j=1}^{J} V_{ij} \quad \text{(eq2)}$$

where $J$ is the total number of forests in the given region. For simplicity, I assumed that only one variable, $D_{ij}$,was the main source of changes in the level of pollination services.

To convert the number of pollinating visitors to the amount of pollination services, I used the value $r$ that represents the success rate of pollination per visit of the pollinator (eq3). This value is particular to the combination of pollinator species and crop species. Equation 3 shows this conversion.

$$P_i = r * TV_i \quad \text{(eq3)}$$

The last equation (eq 4) estimates the crop yield produced at cropland $i$ ($Y_i$) based on the amount of pollination, $P_i$. $Y_i$ is calculated using the carrying capacity of the crop, $Kc$ as follows:

$$Y_i = \frac{Kc}{1 - e^{-(s + t * P_i)}} \quad \text{(eq4)}$$

The parameter $s$ and $t$ are used to adjust the function to make the model more realistic such that crop yield saturates with an appropriate pace at the estimated $Kc$ value. Total yield is calculated by summing $Y_i$ with respect to $i$ because $Y_i$ represents the crop yield at each cropland $i$.

## Constraints

To account for agricultural efficiency and conservation goals, I incorporated three sets of constraints into the model. The first constraint was *conservation constraint* (Box1.a). To satisfy conservation requirement, a certain percentage of the forest must remain undeveloped. The total number of the cells to develop was restricted by the parameter $C$ which represents this minimum percentage of the forest after agricultural development.

The second constraint was *cropland compactness* (Box1.b) to approximate efficient agricultural practices. First, I defined the binary variable, $Z_{ij}$ to identify the adjacency of two cells ($i$ and $j$) of same land covers. Here, $i$ and $j$ are the pairs of cells next to each other (Fischer et al. 2003). As the number of *Z* for croplands increases, the perimeter of the total cropland generally decreases. Because I assume each cell has unit area, I calculated the ratio of area to perimeter for each cropland cell. (Fitzsimmons 2003). By changing the parameter *mc,* I was able to constrain the ratio between zero and one.

The third constraint was *forest compactness* (Box1.c) which is required for both conserving natural habitat and allowing for effective management of croplands. This is essentially the same constraint as for *cropland compactness*, with $(1\text{-}X_j)$ rather than $X_i$ because a cell must be either forest or cropland but not both.

## Optimal spatial model with MINLP

To identify the best arrangement of the croplands in forests for maximum pollination services, I used General Algebraic Modeling System (*GAMS)* (Rosenthal 2008) to assign either forest or cropland to each cell. For this hypothetical model, I made two essential assumptions: (1) Land cover can only be either forest or cropland; and (2) pollinators are the only method for crop pollination (e.g. excluding wind pollination and self pollination). I summed the products of $Y_i$ and $X_i$ with respect to $i$ where $Y_i$ is crop yield defined above and $X_i$ is the binary decision variable. $X_i$=1 indicates forest developed to cropland and forest undeveloped when $X_i$=0. I maximized the total crop yield function (Box1.eq5) under the constraints given above. I optimized my model using Mixed-Integer Non-Linear Programming (MINLP) (Grossmann 2002) in GAMS with BONMIN, solver (Bonami and Lee 2007).

### Box.1 Summary of spatial optimization model.

**Objective Function**

$$\text{Maximize.} \quad \sum_{i=1}^{n} Y_i * X_i \qquad \text{(eq5)}$$

$$Y_i = \frac{Kc}{1-e^{-(s+t*P_i)}} \qquad \text{(eq4)}$$

$$P_i = r * TV_i \qquad \text{(eq3)}$$

$$TV_i = \sum_{j=1}^{J} V_{ij} \qquad \text{(eq2)}$$

$$V_{ij} = Kp * e^{-d*D_{ij}} \qquad \text{(eq1)}$$

**Constraints**

a. Minimum forest requirements constraint for conservation

$$\frac{\sum_{i=1}^{n}(1-X_i)}{n} \leq C \qquad \text{(a)}$$

b. Cropland compactness constraint

$$X_i - Z_{ij} \geq 0 \qquad \text{(b.1)}$$

$$X_j - Z_{ij} \geq 0 \qquad \text{(b.2)}$$

$$X_i + X_j - 1 \leq Z_{ij} \qquad \text{(b.3)}$$

$$\frac{(4 * \sum_{i=1}^{I} X_i - 2 * \sum_{i=1}^{I} Z_{ij})}{4 * \sum_{i=1}^{I} X_i} \leq mc \qquad \text{(b.4)}$$

c. Forest compactness constraint

$$(1 - X_i) - Z_{ij} \geq 0 \qquad \text{(c.1)}$$

$$(1 - X_j) - Z_{ij} \geq 0 \qquad \text{(c.2)}$$

$$(1 - X_i) + (1 - X_j) - 1 \leq Z_{ij} \qquad \text{(c.3)}$$

$$\frac{(4 * \sum_{i=1}^{I}(1 - X_i) - 2 * \sum_{i=1}^{I} Z_{ij})}{4 * \sum_{i=1}^{I}(1 - X_i)} \leq mf \qquad \text{(c.4)}$$

***Variables***

$P_i$: amount of pollination services to cropland *i*, $TV_i$: number of total pollinating visitors to cropland *i*, ***TY***: total yield, $V_{ij}$: number of pollinating visitors from forest *j* to cropland *i*, $X_i$: develop forest *i* when 1, otherwise undeveloped forest *i* (binary decision variable), $Y_i$: amount of crop yield at cropland *i*, $Z_{ij}$: 1 if land *i* and *j* have same land cover type (binary variable for adjacency)

***Parameters***

***C***: proportion of minimum forest requirement for conservation, ***d***: inverse flying ability, ***Kc***: maximum crop density, ***Kp***: forest carrying capacity, ***mc***: compactness determinant for croplands, ***mf***: compactness determinant for forests, ***n***: number of cells in the grid, ***r***: pollination effectiveness, ***s*** and ***t***: additional parameters for yield function

## Analysis

To analyze how each variable and combination of variables affected land arrangement and total yield, I conducted a sensitivity analysis by solving the optimization model multiple times with different parameter values. First, I changed the conservation parameter *C* while holding other parameter parameters fixed (d=0.035, Kp=8.5, Kc=100) to determine what range of the minimum percentage of conserved forest affects most on the optimal landscape for pollination services. I plotted the total yield for 9 of each *C* values from 10 to 90 with an increment of 10.

Next, to determine the effect of the pollinator type, I changed three parameter values, *Kp* (5, 7.5 8.5, 9.5, 12), *Kc* (50, 75, 100, 125, 150), and *d* (0.1, 0.05, 0.035, 0.02, 0.001). I made 5 scenarios for each parameter values and I loop through the each combination of three parameters (125 runs in total). For each trial, I recorded the optimal solution of $X_i$ and Total Yield (*TY*). Then, I depicted the optimal landscape for all results of $X_i$ by using *R* (R Development Core Team 2010, Sarkar 2008), and compared the total yield for each landscape. I also plotted the total yield against each parameter value.

## Results

### General Output

Figure 1 shows the optimal cropland allocation within the forest while maximizing pollination services at the best estimated-values of forest carrying capacity (*Kp*=8.3) and inverse flying ability (*d*=0.0035). To produce maximum crop yield for a pollinator with *d*=0.0035, only 12 units of forest should remained in the center, surrounded by croplands. Each of the 24 cropland cells receives enough pollinators to saturate to the maximum crop density (*Kc*=100) with pollination services. For this configuration, total yield was 2400.

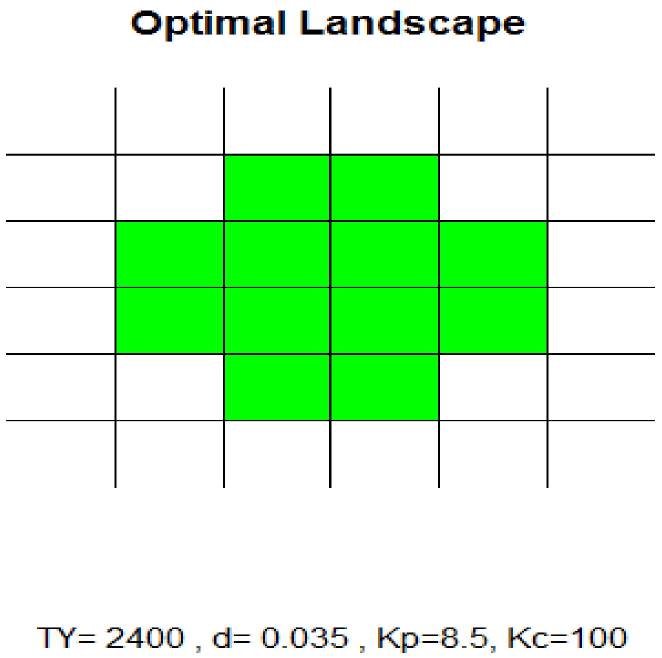

**Figure 1. Optimal land configuration**. At the best estimated parameter values ($d$=0.035, $Kp$=8.5), forest should be in the middle of the area to achieve maximum total crop yield.

## Sensitivity Analysis

### *Minimum conservation area*

I found that the total yield decreased with an increase in minimum conservation area ($C$) while variability of the total yield among different $d$ values also decreased (Fig. 1). However, if $C$ was too small, the total yield was far smaller compared to other $C$ values except $d$=0.1, indicating weaker flying pollinators.

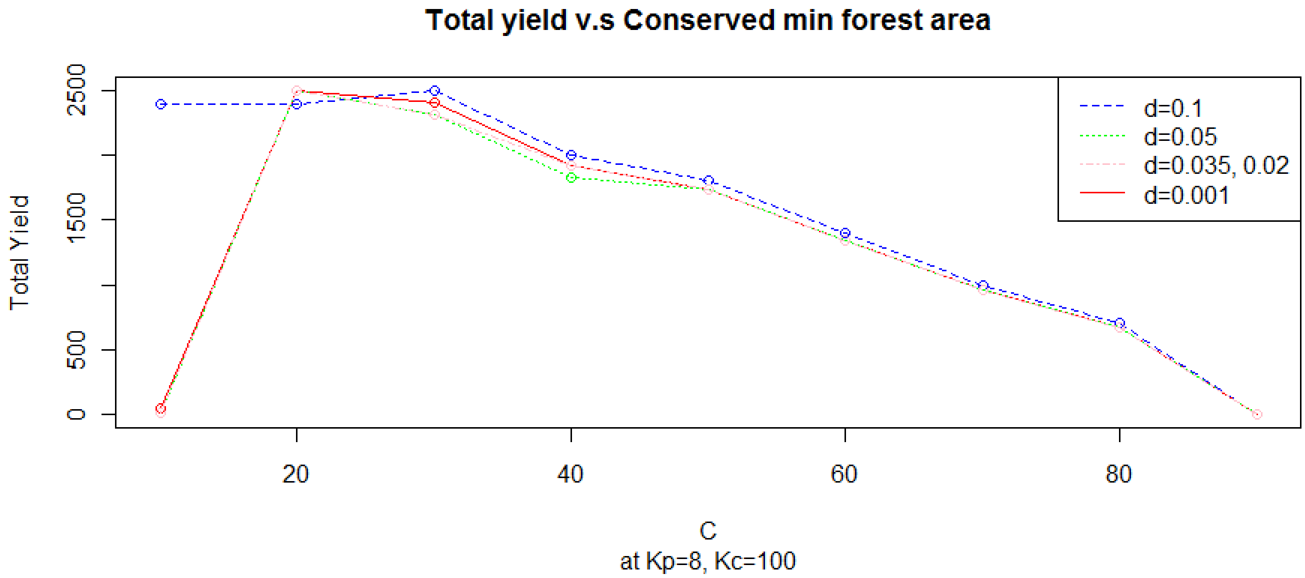

**Figure 2. Total yield with the minimum conservation area.** Total yield generally decreases with the increasing required conservation area (*C*). All except large d produce far smaller crop yield at small *C* values.

### *Forest carrying capacity*

I found that the optimal landscape became more patchy as forest carrying capacity increased (Fig.3). Total yield fluctuated for both values of inverse flying ability [d] around the ceiling value (Fig.2). At low forest carrying capacity (*Kp*=5), the optimal landscape had a forest only in the center when d is small (Fig.3a) while when d is large, the optimal landscape had isolated small forests at corners of the grid area such that all croplands were adjacent to forests (Fig.3b). Total yield was higher when *d* is small (*d*=0.001) than when d is large (*d*=0.1).At high forest carrying capacity (*Kp*=12), the optimal landscape became patchy for both shorter-flying pollinators (*d*=0.1) and longer-flying pollinators (*d*=0.001) (Fig.3c, d). Total yield of weaker-fliers was higher than that of stronger-fliers.

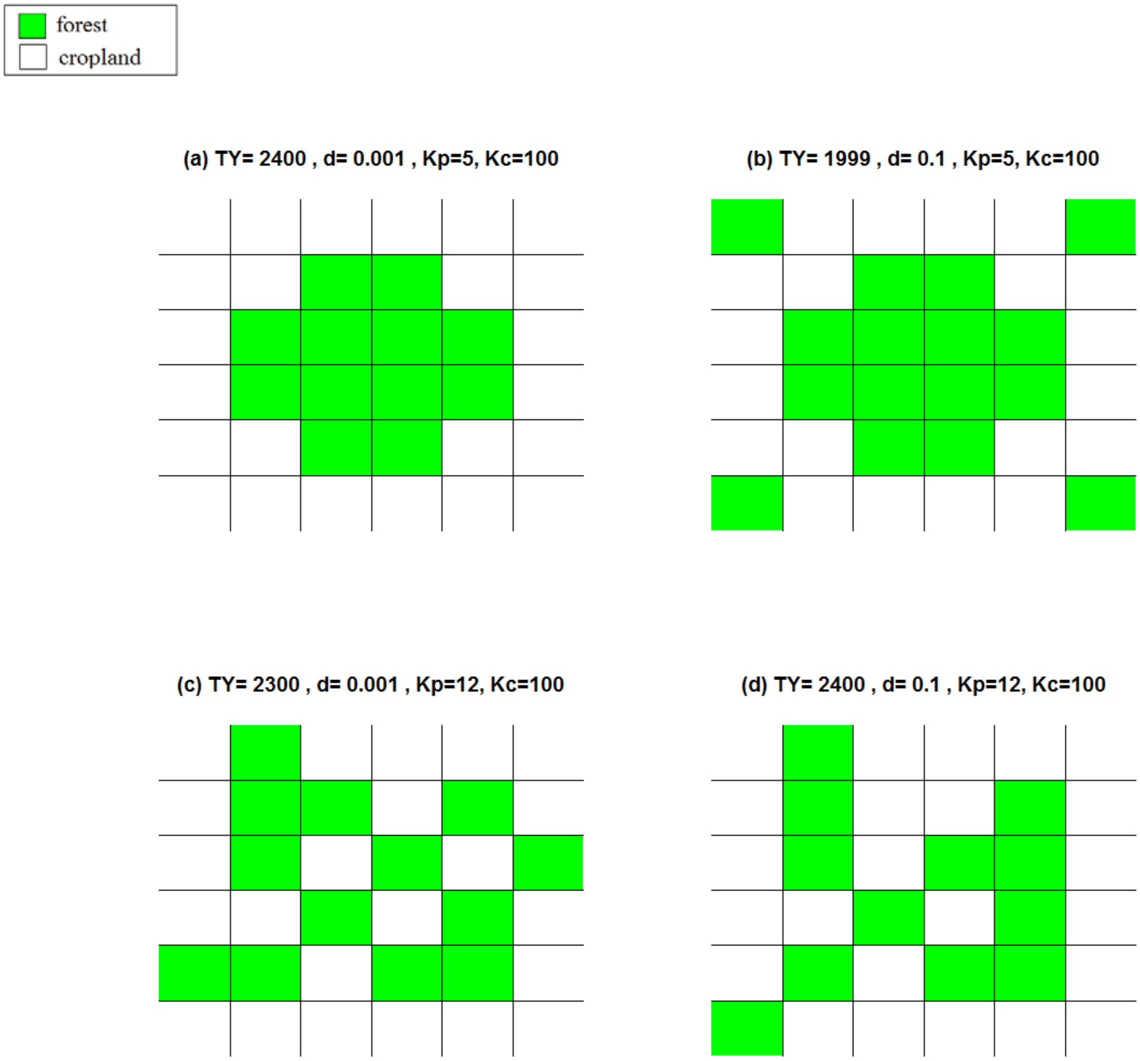

**Figure 3. Optimal landscapes at different forest carrying capacities (Kp) and pollinator types (d)**. The best land cover arrangement were found at (a) small d and small Kp, (b) large d and small Kp, (c) small d and large Kp, and (d) large d and large Kp. Green represents forests and white represents croplands. Small d (0.001) indicates longer-flying pollinators whereas large d (0.1) indicate shorter-flying pollinator. Different Kp values represents different forest types.

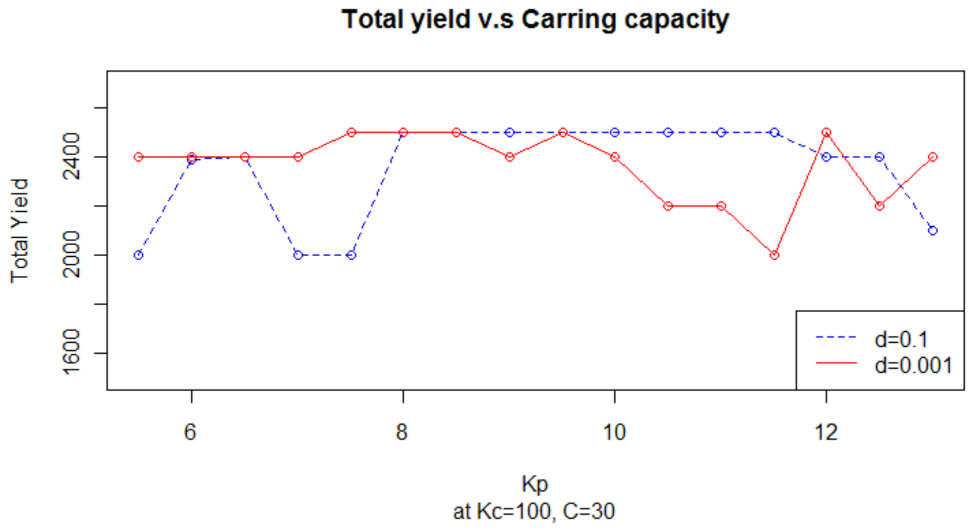

**Figure 4. Total Yield with forest carrying capacity**. At both d values total yield from optimal landscape fluctuates around ceiling crop yield.

### *Maximum crop density*

I found that most maximum crop density (*Kc*) values produced similar landscapes except in a certain range (Fig.5). Total yield was limited by maximum crop density only when pollinators with shorter foraging distances (small d) were present with the crop type having the crop density within the range. The sensitive range of maximum crop density (*Kc*) was between 80 and 130. The optimal landscape with *Kc*=50 (Fig.5.a and b) and *Kc*=150 (e and f), which were out of sensitive range, had similar landscape for each d value (*d*=0.001 and *d*=0.1). The optimal landscape in the sensitivity range at *Kc*=100 had a different pattern from the other two *Kc* values (*Kc*=50, 150) for *d*=0.001 whereas the total yield was limited only for the *d*=0.1.

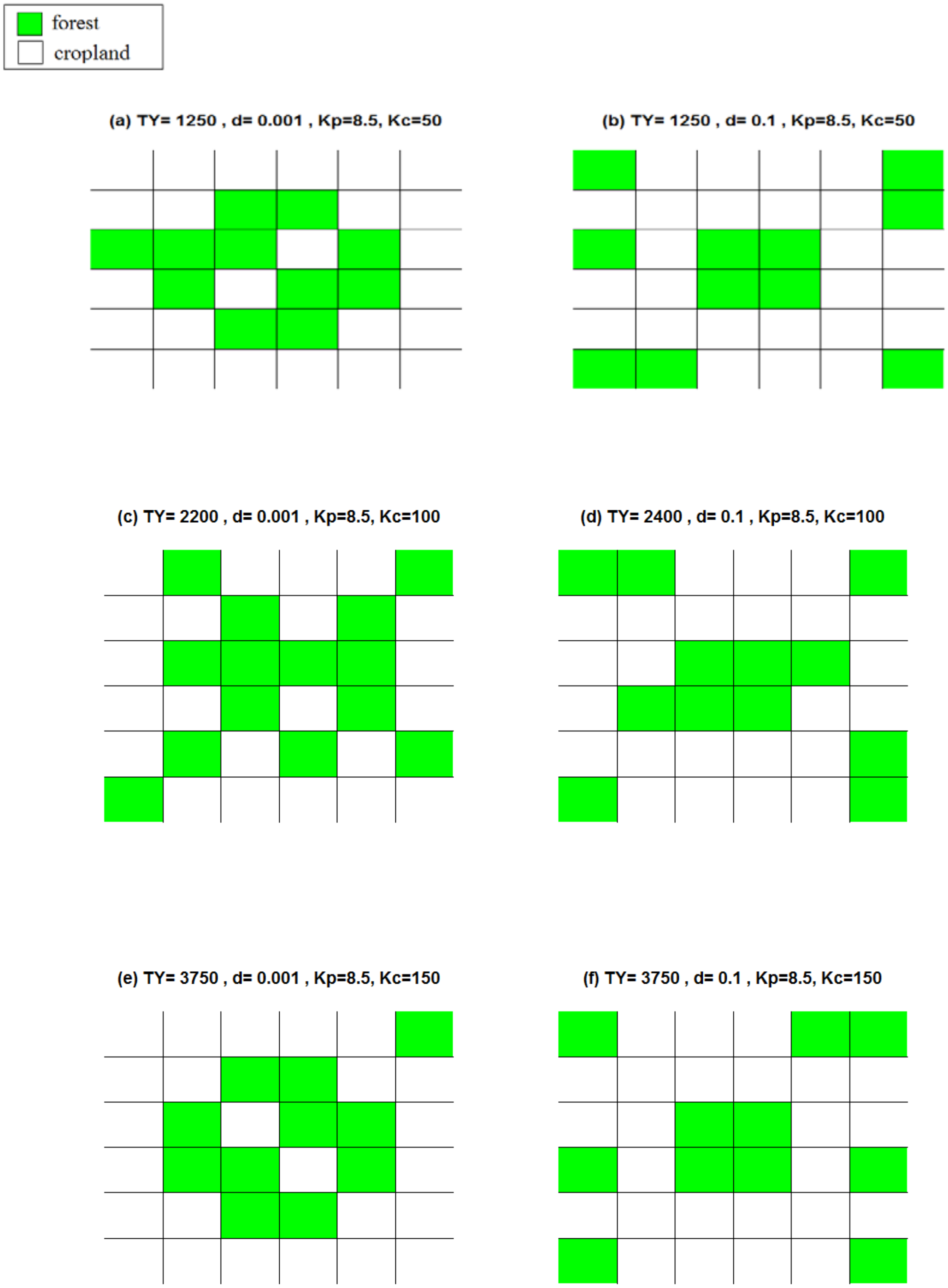

**Figure 5. Optimal landscape at different maximum crop density (Kc) and pollinator types (d)**. The best land cover arrangement were determined at (a)small d and small Kc, (b)large d and small Kc, (c)small d and intermediate Kc, (d)large d and intermediate Kc, (e)small d and large Kc, and (f)large d and large Kc.

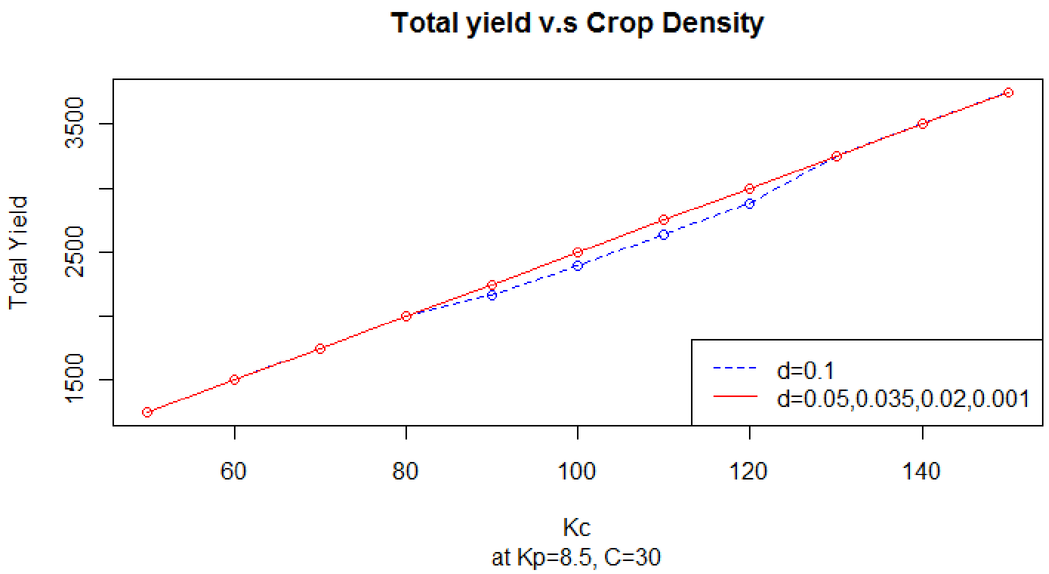

**Figure 6. Total Yield with maximum crop density.** At a certain range of the maximum crop density, the optimal landscape produced less with large *d* than the potential maximum yield.

### *Forest carrying capacity and maximum crop density*

I found that *Kp* affected total yield more than *Kc* at large *d* values, and *Kc* affected total yield more than *Kp* at small *d* values. At a small value of *d* (d=0.001), the difference in *Kp* did not affect total yield very much and total yield increased with *Kc* with the exception of intermediate values of *Kc*=100. At large values of *d* (*d*=0.1), total yield decreased quickly when *Kp* was small.

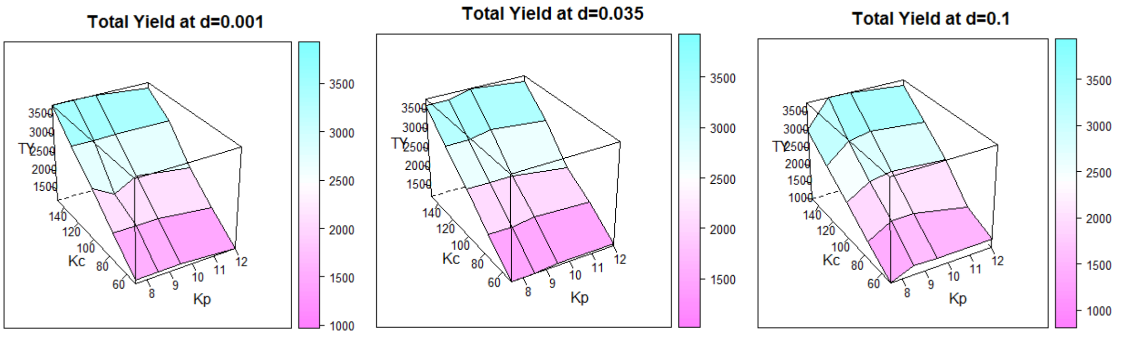

**Figure 7. Twoway sensitivity analysis on Kp and Kc for Total Yield.** The surface was plotted based on the points produced from combinations of five *Kp* (5, 7.5, 8.5, 9.5, 12) values and five *Kc* (50, 75, 100,125, 150) values at three different *d* values (d=0.001, 0.035, 0.1).

# DISCUSSION

Pollination services are a sensitive ecosystem services, largely influenced by pollinator types, crop types, and land configurations. I found that optimal cropland arrangement depends on combinations of the parameters that reflect pollinator type and crop type to maximize the pollination services. I identified a tradeoff between distance effects and area effects. If flying distance of the pollinators is short, then the amount of pollination services will be limited by long distances between habitats and croplands (Ricketts et al. 2008). However, if crop and forest patches are in closer proximity to each other, the area of each cropland and forest decreases, undermining the effective farming practices and limiting crop yield (Brosi et al. 2008). Thus, these two factors must be considered for optimal calculation.

## Different species

Different pollinator types have different optimal landscape configurations for providing pollination services. In recent years, the difference between native pollinators such as stingless bees (*Meliponines*) and bumblebees (*Bombus*) and the managed pollinators, mostly honeybees (*Apis*), is noteworthy for the conservation of natural habitat (Ricketts 2004). The pollinating ability is often measured by physical ability to fly, which is primarily determined by body size and social behavior. Pollinator species with larger body sizes fly longer distances than smaller pollinators. In addition, solitary bees have longer foraging distances than social bees (Steffan-Dewenter and Tscharntke 1999). According to these past findings, social pollinators with small body sizes are the least valuable to the crop production. However, my model showed this is not always the case. The results revealed that shorter-flying pollinators can pollinate better than longer fliers when forest carrying capacity is large (Fig.3c and 3d). It indicates that the value of smaller social bees has been underestimated when presented with a certain forest type.

## Fragmentation, compactness, and productivity

Different sizes and shapes of habitat determine the survival of species in ecology. Quantifying pollination services often considers distances and areas of habitats and croplands (Ricketts et al. 2008). Theories of island biogeography explain the extinction and migration rate from the distances and areas of the habitats (Caughley 1994). Single Large or Several Small (SLOSS) arguments for natural habitats are important to conservation (Atmar and Patterson 1993). Because pollination services are influenced by the isolation of the habitat and patch sizes of the forest, these theories are very useful. While supported from those theories, I limited the ratio of perimeter to area to control the minimum area of the forests. The ratio also controls the shape of the forest to satisfy the given constraint for optimized cropland allocation (Saura and Carballal 2004).

Croplands also must have a limitation on size and shapes because efficient agricultural management is essential for farmers to make a profit (Kleijin et al. 2009 ). Considering both constraints on forest and cropland at the same time is often difficult or ignored in actual agriculture because of the lack of leading authorities having plans and knowledge as well as the physical limitations on the forest development and farming infrastructure (Rozelle et al. 1997).

## Minimum forest area requirements

As required forest area increases, the total crop yield generally decreases. But the rate of decrease is slightly different for each pollinator’s flying ability. At the very small forest area requirement, the crop yield is far smaller due to the limitation of the compactness constraint. Small forests cannot support enough pollinators to saturate crop yield. Thus, a certain amount of forest had to remain not only for conservation but also for the source of pollination services (Klemen et al. 2004). When the minimum forest requirement increases by a small amount, the total yield dramatically improved to produce the maximum yield. The yield generally decreases as required forest area increases, because the land that could be used for the cropland had to be forgone for the forest conservation (Priess et al. 2007). The variability of the total yield among pollinator types decreases as the forest requirement increases.

## Forest carrying capacity

The combination of forest carrying capacity for the pollinators and the flying ability of the pollinator determines the optimal landscape and the level of total yield. If pollinators can fly longer distance, as the forest carrying capacity increases, pollination services increase until it reaches the maximum crop density for each cropland. When it reaches this ceiling, forest carrying capacity does not affect the yield for each cropland. Rather, total yield fluctuates around the carrying capacity due to the effect of the compactness constraints and the binary decision variable (Fig.4). If the pollinators have shorter flying distance, the optimal landscape needs more forests to maximize pollination services (Fig.3b). Also, a higher carrying capacity is required to reach the yield associated with that carrying capacity for each cropland. After reaching the ceiling, the total yield should be similar to scenarios with longer-flying pollinators. Thus, a pollinator's type does not affect the total yield at when carrying capacity is large.

The mathematical mechanism for this has several parts. As the carrying capacity of the forests increases, the number of pollinators visiting each cropland increases. Thus, the crop yield in each cropland saturates with pollination services at the maximum crop density when the forest carrying capacity is large. However, if carrying capacity is too large, a portion of the forest is not required especially for the pollinators with longer flying ability. Then, optimization decreases the forest due to the increasing carrying capacity to increase the cropland area. This might violate the forest compactness constraint if the reduced forest is adjacent to another forest unit. In that case, rearrangement of the forests occurs and the maximized total yield may not increase proportional to increased cropland area.

Although the carrying capacity is particular to the forest type and might appear beyond the reach of management, there are several ways to increase the nesting sites for pollinators. Disturbance and open areas caused by forest development make more space for foraging flowers (Ricketts 2004). Because forest land itself usually does not have many flowers for pollinators, making flower sources near the forest other than crops may increase the carrying capacity of the forest. But stakeholders have to be aware of the competition for pollinators between those flowers and crop flowers (Holzschuh et al. 2011). Another way is to increase forest perimeter length adjacent to croplands because more adjacency increases opportunity to reach more flowers, and pollinators thrive (Chacoff et al. 2006). But we must take it into consideration that increasing edge ratio may be the potential risk for sensitive species (Laurance and Yensen 1991).

### Maximum crop density

The crop with higher flower density feeds more pollinators and raises its population. (Westphal et al. 2003). Increasing crop floral density increases the maximum yield per unit area. If more than the limit of pollination services is provided, total yield increases proportional to the increase in maximum crop density (Brown et al. 2002). If the amount of pollination services is less than the carrying capacity, crop density does not limit the total yield. In the range of maximum crop density levels, different flying abilities of the pollinators limit the total yield. Total yield is more limited by shorter foraging pollinators (Taki et al. 2010). So the increase rate of the total yield with crop density is less in weaker fliers than in stronger fliers.

No crop preferences occur when the pollinators are strong fliers because the flexible land arrangement is possible to overcome the decreasing crop density. In contrast, the farmer or agricultural planner should take care in crop selection when the pollinators are weaker fliers because land arrangement is not subject to change due to the pollinator type.

### Limitations

This model is sensitive to four model building assumptions as well as limits in the literature for estimation of parameters. The first assumption is that only two land cover alternatives exist, cropland or forest. This assumption limits the habitat types for pollinators to only forest. In nature, pollinators nest in various land types and this flexibility stabilize the supply of pollination services (Freitas and Sazima 2006). The second assumption is that only one type of pollinator exists in the forest, and there are not any pollinators nesting in the cropland. This assumption is held in many cases when one species dominates pollination (Rader et al. 2009). Otherwise, the narrow variety of pollinator types results in positive biodiversity effect due to the insurance theory of biodiversity (Bluethgen and Klein 2011). I only used one out of two types of pollinators at a time to compare the different types of pollinators for parameter $d$. However, if more than one pollinator coexists in this model, the result would be different due to interspecific resource conflicts (Paini 2004). The third assumption is that animal pollinators are the only pollinating method: I excluded wind and self-pollination. This assumption limits the range of application of this model to only pollinator-dependent crops. Many major essential crops defined by FAO such as corn, rice, and wheat are actually wind-pollinating crops (Klein et al. 2007). The fourth assumption is that only two factors, area and distance, change the amount of pollination services. This assumption is necessary to keep the model simple and make it possible to analyze the mechanism of the pollination services.

## Future applications

This model was originally designed to assess the biodiversity effects on pollination services. There are two ways to customize this model to incorporate biodiversity. One approach is to introduce other habitat types in addition to the forest and cropland (define another *K* similar to *Kp* and *Kc*) to increase the habitat diversity for pollinators. The other approach is to introduce new pollinator types equaling that multiple flying ability parameters (*d*) are used. It would help supply the stable amount of pollination based on the insurance hypothesis of biodiversity (Naeem and Li 1997). This model can test the hypothesis of biodiversity in the context of optimizing land arrangement for agriculture.

To make the model more practical, we can assign different parameter values at different proximities to each type of land cover. For example, the carrying capacity of the forest for pollinators is known to be a decreasing gradient from the edge of the forest because a cleared area (cropland) provides many more flowers for pollinators to forage. Database usage might be critical factor too to provide different solutions fit to specific regions. For instance, the sizes and types of the pollinator affect the flying distance of pollinators (*d*). And each region has different types and sizes of pollinators. If the geo-database of pollinators and forest types are available and fully utilized, the best fit parameter values could be estimated from the database for different regions.

## Broader implications

This model contributes to the sustainable development of tropical forests for agriculture that can be used by a number of stakeholders in the system. For example, policy makers and land developers can generate blueprints of how they should develop forest areas and plan agricultural development with this model, and local farmers could increase profits by changing the land configuration of the crops according to this model. More importantly specific plans can be virtually tested before deforestation starts by adjusting parameter values customized to their environment contributing to the conservation of the forest. In the larger sense, this model integrates various levels and fields of science into one informative solution for sustainable development. I expect this model to help to ensure the livelihoods of local farmers as well as a stable supply of crops in the global market by improving yield efficiency of agroforestry.

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# APPENDIX A: GAMS Code

```
Sets
i number of the cell i /1*36/
alias(i,j);

set
z(i,j) paired sets for adjacency /

1.2, 2.3, 3.4, 4.5, 5.6, 7.8, 8.9, 9.10, 10.11, 11.12, 13.14, 14.15, 15.16, 16.17, 17.18, 19.20, 20.21, 21.22, 22.23,
23.24, 25.26, 26.27, 27.28, 28.29, 29.30, 31.32, 32.33, 33.34, 34.35, 35.36,
1.7, 2.8, 3.9, 4.10, 5.11, 6.12, 7.13, 8.14, 9.15, 10.16, 11.17, 12.18, 13.19, 14.20, 15.21, 16.22, 17.23, 18.24, 19.25,
20.26, 21.27, 22.28, 23.29, 24.30, 25.31, 26.32, 27.33, 28.34, 29.35, 30.36/;

Parameters
n number of cells /36/
Kc carrying capacity for crops /100/
a adjasting param 1 /20/
b adjusting param 2 /0.6/
*Need to estimate these three values
Kp carrying capacity for pollinators /8.2367/
*exp(2.1086)
dd pollinators ability to fly /0.0035/
r rate of dependence on  pollinators /0.8/
c % of forest remain /30/
m1 management constraint /0.8/
m2 /0.8/
*Changing the size of the cropland by sum of adjacency;

Table D(i,j) distance from cell i to cell j ; omitted

Variables
X(i)  develop i
* if develop then 1
Y(i)  yield for each cell i
P(i)  pollination for each i
V(i,j) Visitors from forest j to cell i
Zp(i,j) adjacency
Zp2(i,j)
*if i and j are adjacent then 1
*bool_eqv(X(i),X(i))
ZT
ZT2
TY total yield;

Binary variable X(i), Zp(i,j),Zp2(i,j) ;
Positive variable Y(i),P(i), V(i,j) ;

Equations
        TotalYield      define objective function of total crop yield
```

```
        Yield(i)      yield for each cell i
        Pollination(i)  pollination services to cell i
        Visitors(i,j)   number of visitors from forest j to cropland i
        Conservation    at least **% of forest must remain
        Adjacency1(i,j) define adjacency 1
        Adjacency2(i,j) define adjacency 2
        Adjacency3(i,j) define adjacency 3
        AdjTotal       total# of adjacency
        AdjRatio       Adj constraint
        Adjacency21(i,j) define adjacency 1
        Adjacency22(i,j) define adjacency 2
        Adjacency23(i,j) define adjacency 3
        AdjTotal2       total# of adjacency
        AdjRatio2       Adj constraint;

TotalYield ..      TY =e= sum(i, X(i)*Y(i)) ;
Yield(i) ..       Y(i) =e=  Kc/(1+exp(a-b*P(i)))   ;
Pollination(i) ..  P(i) =e= r*sum(j, V(i,j));
Visitors(i,j) ..   V(i,j) =e= (1-X(j))*exp(-dd*D(i,j))*Kp;
Conservation ..    sum (i, (1-X(i)))/n *100 =g= c ;
Adjacency1(z(i,j))  ..    X(i)-Zp(z) =g= 0       ;
Adjacency2(z(i,j))  ..    X(j)-Zp(z) =g= 0       ;
Adjacency3(z(i,j)) ..     X(i)+x(j)-1 =l= Zp(z);
AdjTotal ..               ZT =e= sum(z, Zp(z))        ;
AdjRatio ..              (4*sum(i, X(i))-2*ZT) =l= 4*sum(i, X(i))*m1 ;
Adjacency21(z(i,j))  ..    (1-X(i))-Zp2(z) =g= 0       ;
Adjacency22(z(i,j))  ..    (1-X(j))-Zp2(z) =g= 0       ;
Adjacency23(z(i,j)) ..     (1-X(i))+(1-x(j))-1 =l= Zp2(z);
AdjTotal2 ..               ZT2 =e= sum(z, Zp2(z))        ;
AdjRatio2 ..              (4*sum(j, (1-X(j)))-2*ZT2) =l= 4*sum(j, (1-X(j)))*m2 ;

Model simple /all/;
option minlp = bonmin ;
solve simple using MINLP maximizing TY;
display X.l, TY.l;

*Create a set of scenarios to explore the effects of changing the "c" assumption
*In this example, I consider six values...

Sets ScenarioKc Scenario Set for c /S0*S4/ ,
    ScenarioKP Scenario set for kp /T0*T4/
    Scenariodd /U0*U4/

Parameters
         kpnew(ScenarioKP) carrying capacity for polinators /T0 5, T1 7.5, T2 8.5, T3 9.5, T4 12/
         Kcnew(ScenarioKc) maximum crop yield / S0 50, S1 75, S2 100, S3 125, S4 150 /
         ddnew(Scenariodd) pollinator flying ability /U0 0.1, U1 0.05, U2 0.035, U3 0.02, U4 0.001/;

*Organize Results by scenario
Parameter output_x(i,ScenarioKp, ScenarioKc, Scenariodd) Develop Results,
        Output_TY(ScenarioKp, ScenarioKc, Scenariodd)  Total Yield Results,
        Output_Kc(ScenarioKc)   Max yield,
        Output_kp(ScenarioKP)   Carrying capacity
```

```
        Output_dd(Scenariodd)   Flying ability  ;

loop((ScenarioKp, ScenarioKc, Scenariodd),
       Kc=Kcnew(scenarioKc) ;
       Kp=kpnew(scenarioKP) ;
       dd=ddnew(Scenariodd) ;

solve simple using MINLP maximizing TY;
Output_X(i,ScenarioKp, ScenarioKc, Scenariodd) = X.L(i) ;
Output_TY(ScenarioKp, ScenarioKc, Scenariodd) = TY.L ;
Output_Kc(ScenarioKc) = Kc   ;
Output_kp(scenarioKP) = kp ;
Output_dd(Scenariodd) = dd ;);

execute_unload 'solution.gdx',Output_X,Output_TY,Output_Kc,Output_kp,Output_dd ;
execute_unload 'C:\GAMS_Solutions\solution.gdx',Output_X,Output_TY,Output_Kc,Output_kp,Output_dd ;

execute 'gdxviewer.exe i=C:\GAMS_Solutions\solution.gdx csv=C:\GAMS_Solutions\X.csv id=Output_X';
execute 'gdxviewer.exe i=C:\GAMS_Solutions\solution.gdx csv=C:\GAMS_Solutions\TY.csv id=Output_TY';
execute 'gdxviewer.exe i=C:\GAMS_Solutions\solution.gdx csv=C:\GAMS_Solutions\Kc.csv id=Output_Kc';
execute 'gdxviewer.exe i=C:\GAMS_Solutions\solution.gdx csv=C:\GAMS_Solutions\Kp.csv id=Output_kp';
execute 'gdxviewer.exe i=C:\GAMS_Solutions\solution.gdx csv=C:\GAMS_Solutions\dd.csv id=Output_dd';
```