Estimating landscape structure effects on pollination for management of agricultural landscapes

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Abstract

The present study aims to examine the effects of habitat fragmentation to find a pattern of forest patches in agricultural landscapes that provide the highest pollination level. For this purpose, using simulated agricultural landscapes, including different forest proportions and degrees of fragmentation, pollination in different scenarios was estimated. We used landscape metrics to measure the landscape composition and configuration of each simulated landscape and estimated their statistical relationship with pollination. Our results showed that the effects of fragmentation on pollination were affected by two significant factors; 1- habitat amount and 2- small patches' capacity to supply pollination. Our results showed that when small patches' capacity in supplying pollination was low, fragmentation decreased pollination. When this capacity was very high, landscapes with a high degree of fragmentation showed higher levels of pollination. There was an exception for habitat amounts less than 0.1 of the entire landscape that increasing edge density, aggregation, and the number of patches, resulted in increasing pollination in all scenarios.

Introduction

Approximately 9.5% of the world's agricultural production comes from the services provided by wild bees (Gallai et al., 2009). Recent studies have shown that bees are more efficient pollinators than other pollinators because they both visit more flowers and put more pollen on the flower's stigma (Willmer et al., 2017). Therefore, the most important pollinators are bees, which are directly responsible for maintaining the diversity of native vegetation, and many plants depend on these pollinators for their reproduction (Ollerton et al., 2011). Wild bees required two basic needs; 1- nesting habitat, and 2- foraging habitat (Olsson et al., 2015; Ricketts et al., 2008), and need their nesting and foraging habitats to be adjacent (Kline and Joshi, 2020). In agricultural landscapes, pollination depends on the movement of native pollinators from non-agricultural areas such as forests (nesting habitat) to farms (foraging habitat) (Ricketts et al., 2008).

It is acknowledged that the abundance of wild bees and their diversity on farms, depends on the distance between their nesting and foraging habitat patches (Ekroos et al., 2013; Gathmann et al., 1994; Ricketts et al., 2008; Steffan-Dewenter, 2002; Steffan-Dewenter and Schiele, 2008). Several studies have shown that pollination decreases exponentially with increasing distance from natural and semi-natural forest patches within agricultural fields (Keitt, 2009; Martins et al., 2015; Mitchell et al., 2015; Ricketts et al., 2008). For example, Ricketts et al. (2008) reviewed 23 studies examining the effects of landscape structure on pollination. They found that the abundance and visiting rate of pollinators decreased exponentially as the distance from the nesting habitat increased. The distance that bees can travel affects their ability to pollinate. The foraging distance varies according to the species and body size (Everaars et al., 2018). For example, *A. Mellifera* can travel up to 1100 meters (Gary et al., 1981), but most bees move short distances below their maximum capacity, in fact, something between 100 and 300 meters (Greenleaf et al., 2007; Zurbuchen et al., 2010). In many agricultural landscapes, the abundance and diversity of bees are reduced at distances of 50 to 500 meters from forest patches (Bailey et al., 2014). For example, for the coffee plant, pollination is reduced by increasing distance from forest patches (Boreux et al., 2013; Klein et al., 2003; Krishnan et al., 2012; Ricketts et al., 2004; Saturni et al., 2016). Therefore, wild bees only pollinate the crops that are within their foraging distances (Ricketts et al., 2006).

It is possible to manage the ecosystem services provision by creating new patches and controlling their location (Fahrig et al., 2011). Therefore, creating new vegetation in a landscape is an issue that deserves to be considered as a research priority (Munro et al., 2009; Thomson et al., 2009). The effects of changing the location and size of natural habitats like a forest in providing pollination to the surrounding agricultural lands have not been studied (Mitchell, 2014). How much habitat is needed and how it should be distributed within an agricultural landscape is the most important question in this area (Brosi et al., 2008b). To increase pollination in an agricultural landscape, it is necessary to identify suitable areas for creating new forest patches in the landscape. For this purpose, estimating the relationship between pollination and landscape structure helps us to determine prerequisites for increasing pollination in an agricultural landscape (Syrbe and Walz, 2012). Maurer et al. (2020) also emphasized the importance of studying the effects of fragmentation on pollinators to guide the spatial optimization of landscapes to increase pollination. Since it is difficult and time-consuming to examine the effects of creating new forest patches in an agricultural landscape, simulation-based studies are recommended (Häussler et al., 2017).

Some studies have shown high pollination rates in fragmented patterns (Brosi et al., 2008a). However, other studies have found adverse effects of fragmentation on pollination. For example, Farwig et al. (2009) reported a decrease in pollination success in landscapes with high isolation of forest patches. Aguilar et al. (2006) also found that reducing the patch size and increasing the isolation of the patches adversely affected pollination. They reviewed 54 studies examining the effects of fragmentation on plant reproduction and found adverse effects of fragmentation on reproduction, mainly due to fragmentation effects on pollinators. It is claimed that pollination provision occurs when natural and unnatural habitats have some juxtaposition, and this juxtaposition occurs when there are some habitat loss and fragmentation in the landscape (Eigenbrod, 2016). Mitchell et al. (2015) also predicted that the highest levels of pollination occurred in landscapes with moderate habitat amounts and fragmentation levels. Some theoretical studies have claimed that adverse effects of habitat fragmentation are more impressive when habitat amount is low, mainly in landscapes that habitat covers less than approximately 20–30% of the entire landscape, known as fragmentation threshold (Fahrig, 2003; Maurer et al., 2020; Rybicki and Hanski, 2013). For example, At low habitat amounts, Maurer et al. (2020) reported the adverse effects of fragmentation on bumblebee colony size. However, they found positive effects at high habitat amounts. Bee foraging activity also increased in the landscapes with a low degree of fragmentation. They concluded that the effects of fragmentation were strongly dependent on habitat amount in the landscape.

The main purpose of the present study is to find an optimized pattern of forest patches for increasing pollination in an agricultural landscape in northern Iran. Land managers want to know what factors are essential for increasing pollination by creating new forest patches in the study area. The most important question that they want to know is; which pattern of forest patches provides the highest pollination level in the landscape? As mentioned above, it is unclear what degree of fragmentation leads to the highest pollination rate in a given habitat amount. Therefore, it is necessary first, to predict these effects using simulated landscapes and then determine the pattern that provides the highest pollination level for the landscape under study according to the obtained results. As far as we are aware, no study has tried to respond to the question using simulated landscapes and modeling the effects of fragmentation on pollination in a constant amount of habitat. Like previous studies, the present study also assumes that forest patches provide nesting habitats for pollinating bees from which they go to the surrounding farms for pollination.

Methods

Generating simulated landscapes

Many studies have simulated the ecological processes of landscapes using computer models. Compared to real-world landscapes, simulated models have fewer limitations and enable us to examine certain aspects of a landscape. In the present study, we generated simulated agricultural landscapes, including two classes of forest and agriculture. Using the NLMR package (Sciaini et al., 2018) in R software, maps with dimensions of 50 by 50 cells with different proportions of forest habitat and degrees of fragmentation were produced. The proportions of forest habitat were variable from 0.05–50% (0.05, 0.1, 0.2, 0.3, 0.4, and 0.5) of the entire landscape. At each of these proportions, the degree of fragmentation changed from highest (0.01) to lowest (0.5) using parameter p (the proportion of elements randomly selected to form clusters) in the NLMR package.

Estimating pollination in simulated landscapes

Large patches maintain more pollinators (Tscharntke and Brandl, 2004), and pollinators' abundance decreases, as the size of the patches decreases (Aguirre and Dirzo, 2008). Pollinators' abundance also decreases as the distance from large patches increases (Donaldson et al., 2002; Joshi et al., 2016; Mitchell et al., 2014; Ricketts et al., 2008). Therefore, one of the assumptions of the present study is that pollination rate is a function of the patch size and larger patches provide more services than smaller patches. The potential of a patch to provide pollination is calculated according to the following equation between 0 and 1 (Mitchell et al., 2015).

$$\boxed{N_{j=1-exp\left[-\left(A_j*p\right)\right]} \qquad 1}$$

Where A_j represents the patch area and P is a fixed number to determine the curve steepness. Using this equation, the ecosystem service supply for each patch is calculated according to its area. Increasing P gives the small patches more capacity to provide pollination. In the present study, we used different values of P (0.001, 0.008, 0.02, 0.08, and 0.16) to better adapt our results to the real conditions in nature (Mitchell et al., 2015).

As mentioned above, the pollination flow decreases exponentially with increasing distance from the desired patches. Pollination flows from forest patches to surrounding farms by the following equation (Mitchell et al., 2015).

$$\boxed{\sum ij\left(d\right) = N_j * 2^{-\left(\frac{d}{d_{1/2}}\right)^2}}$$

Where N_j is the value that extends from the desired patch to the surrounding environment. $d_{1/2}$ is a constant that determines the distance at which the pollination service rate reaches 1/2 of its original value. In the present study, we used different distance values of 5, 10, 15, and 20 cells from the edge of the patches to identify the effects of distance change on the pollination behavior.

Landscape metrics

Landscape metrics measure two fundamental aspects of landscape structure: composition and configuration. Landscape composition refers to the variety and abundance of patch types regardless of their spatial distribution. Landscape configuration refers to the spatial elements or distribution of landscape components (Leitão et al., 2012). In the present study, six commonly used metrics were calculated for all simulated landscapes using Fragstats software (McGarigal et al., 2002) at the class level (Table 1). The Pearson correlation was used to determine the degree of dependency of pollination variations to landscape patterns.

Table 1
Descriptions of the selected landscape metrics.

Category	Metric	Equation	Range
Area and Edge			
	Area-MN	$\frac{\sum_{j=1}^{n} x_{ij}}{n_i}$	Area-MN > 0
	ED	$\frac{\sum e_{ik}}{A}(10000)$	0 ≤ ED, no limit
Shape	PAFRAC	$\frac{2}{\frac{\left[\sum_{j=1}^{n} lnp_{ij} - lna_{ij}\right] - \left[\left(\sum_{j=1}^{n} lnp_{ij}\right)\left(\left(\sum_{j=1}^{n} lna_{ij}\right)\right)\right]}{\left(\sum_{j=1}^{n} lnp_{ij}^{2}\right) - \left(\sum_{j=1}^{n} lnp_{ij}\right)^{2}}}$	1 ≦ PAFRAC ≦ 2
Aggregation	AI	$\left(\frac{g_{ii}}{max \to g_{ii}}\right)(100)$	0 ≤ AI ≥ 100
	NP	n_i	NP ≥ 1
	ENN	h_{ij}	ENN > 0

Note: a_{ij}=area (m^2) of patch; A = total landscape area (m^2); n_i=number of class i patches in the landscape; e_{ij}=total length (m) of edges of patch ij, including landscape boundary, g_{ii} = the number of adjacencies (contiguity) between pixels of patch class i; max g_{ii} =maximum possible number of adjacencies among pixels of patches of class i, h_{ij} = distance (m) from patch ij to the nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center (McGarigal et al., 2002)

Using a genetic algorithm for creating new forest patches in the study area

In the present study, a genetic algorithm was used to optimize pollination by creating new patches in the study area, consisting of two forest and agricultural ecosystems. Genetic algorithm is one of the most widely used methods in finding the optimal solution among the countless solutions for land planning (Matthews et al., 2006) and is based on evolutionary calculations (Mitchell et al., 1994). Eq. 2 was considered as the goal function of the genetic algorithm, and the purpose was to maximize this function in different P. We also considered the spatial scale effects on the new patches' location. Therefore, this process was performed in four spatial scales with different total landscape areas and forest proportions. For each landscape, the rate of increasing forest patches was considered 5% of the total selected landscape (Fig. 2).

Results

Effects of small patches capacity on pollination service

Fig. 3 illustrates pollination changes according to the degree of fragmentation in different forest proportions and P. In this figure, horizontal axes show the degree of fragmentation that decreases from 0.1 to 0.5. Vertical axes indicate estimated pollination at the farm level. Concerning this figure, pollination behavior was both linear and non-linear according to changes in landscape structure patterns. The behavior did not change due to the distance from forest patches or the bees' foraging range. The small patches' capacity in supplying pollination and the proportion of forest patches were only affecting factors determining the position of the maximum pollination rate on graphs (Fig. 3).

At p = 0.001 (low capacity of small patches in supplying pollination) in all forest proportions (0.05, 0.1, 0.2, 0.3, 0.4, and 0.5) of the total landscape, high levels of forest fragmentation declined pollination. In proportions less than 0.3, this behavior was linear, and In proportions 0.4 and 0.5, the shape of the behavior changed and became non-linear. At p = 0.004 and 0.008 in proportions less than 0.3, an increase in fragmentation led to a decrease in pollination. In proportions 0.4 and 0.5, the pollination behavior changed slightly and became non-linear, in which the maximum pollination rate in 0.5 occurred at the moderate degrees of fragmentation. At p = 0.02 in all proportions, pollination behavior changed nonlinearly and altered the position of the maximum pollination rate on the graph (Fig. 3). At p = 0.08, in proportions less than 0.2, the maximum pollination level occurred at the moderate range of forest fragmentation. In proportion 0.5, the maximum pollination level occurred in landscapes with the highest fragmentation level. At p = 0.16 (high capacity of small patches in supplying pollination), in the proportions 0.05 and 0.1, the maximum pollination rate occurred at the moderate degrees of fragmentation. In proportions greater than 0.3, the maximum pollination rate occurred in the highest fragmentation level. Generally, the most notable result was that in the low capacities of small forest patches in supplying pollination, the maximum pollination level happened in the landscapes with a high degree of fragmentation. It should be emphasized that the high capacities of the small patches changed the result completely.

The relationship between landscape metrics and pollination

Table 2 shows the results of correlation analysis between pollination and landscape metrics in different P and forest proportions. The statistical analysis indicated that the capacity of small patches in supplying pollination and different forest amounts affected the effects of fragmentation on pollination considerably. In each habitat proportion with a specific value of P, the relationship between landscape metrics and pollination was different. As fragmentation decreases, the number of patches (NP), edge density (ED), and the perimeter-area ratio (AREA_MN) of the patches decreases, while the average distance between the patches (ENN-MN) and the patches' aggregation (AI) increases.

The AI measures the aggregation degree of patches, and it is high when patches have an aggregated pattern. The AI metric showed a strong positive correlation with pollination at P less than 0.008 in all proportions. By increasing P to 0.08, the relationship was positive only in proportions less than 0.2 and negatively correlated with pollination in proportions greater than 0.2. This result was also the same for P = 0.16. The negative correlation between the number of patches (NP) and pollination showed that for P less than 0.008 in all proportions decreasing the number of patches increased pollination. In proportions greater than 0.2 when P was higher than 0.8, the result was different (Table 2). The positive correlation between the ENN_MN and pollination showed that at P less than 0.008 increasing distance between forest patches increased pollination. LPI and AREA MN showed a positive correlation with pollination at P less than 0.08 in all proportions, implying that increasing the patch area can increase pollination. In P higher than 0.08, this result was different. ED and PAFRAC had a strong positive correlation with pollination. The results of these metrics showed that at P less than 0.008, increasing the edge density and shape complexity of patches reduced pollination and by increasing the P, this effect was reversed. However, for proportions less than 0.1 there were exceptions for both metrics (Table 2).

Table 2. Correlation between landscape metrics and pollination in different habitat areas

	Proportion	PAFRAC	ED	AREA_MN	ENN_MN	NP	AI
P=0.001	0.05	0.66	-0.98	0.85	0.87	-0.96	0.98
	0.1	0.46	-0.99	0.85	0.88	-0.97	0.99
	0.2	-0.70	-0.96	0.92	0.92	-0.90	0.96
	0.3	-0.92	-0.94	0.97	0.96	-0.85	0.94
	0.4	-0.79	-0.95	0.84	0.77	-0.94	0.95
	0.5	-0.65	-0.97	0.71	0.55	-0.93	0.87
P=0.008	0.05	0.72	-0.97	0.76	0.78	-0.98	0.97
	0.1	0.55	-0.96	0.68	0.71	-0.99	0.96
	0.2	-0.58	-0.93	0.74	0.75	-0.96	0.96
	0.3	-0.57	-0.86	0.55	0.52	-0.92	0.86
	0.4	-0.18	-0.57	0.20	0.08	-0.74	0.57
	0.5	-0.83	-0.08	0.85	0.73	-0.97	0.97
P=0.08	0.05	0.68	-0.50	0.003	-0.03	-0.64	0.50
	0.1	0.37	-0.31	-0.23	-0.19	-0.48	0.31
	0.2	0.46	0.32	-0.75	-0.74	0.12	-0.32
	0.3	0.89	0.75	-0.97	-0.98	0.58	-0.75
	0.4	0.90	0.71	-0.94	-0.97	0.52	-0.71
	0.5	0.94	0.82	-0.96	-0.98	0.65	-0.82
P=0.16	0.05	0.53	-0.24	-0.27	-0.24	-0.40	0.24
	0.1	0.22	-0.07	-0.45	-0.42	-0.24	0.06
	0.2	0.59	0.59	0.91	-0.90	0.41	-0.59
	0.3	0.95	0.90	-0.99	-0.99	0.78	-0.90
	0.4	0.96	0.86	-0.99	-0.99	0.71	-0.86
	0.5	0.96	0.89	-0.99	-0.98	0.74	-0.89

Increasing pollination by creating new forest patches

Fig. 4 shows the location of the new patches created by the genetic algorithm at four spatial extend. In this part of the research, the aim was to determine the location, shape, and number of new forest patches in the study area to increase pollination. Column A (Fig. 4) shows the original images without any change, column B shows the created patches at P= 0.001, and column C shows the created patches at p = 0.16. The results of this section also showed that when the capacity of small forest patches in supplying pollination was low, the created patches were distributed sparsely in the landscape. As the capacity of the small patches increased, the new patches were created near the original natural patches. This result is well visible in subset 1. The change in spatial scale caused a shift in the created patches' location in each subset, as predicted. As the spatial extent increased, the proportion of the original habitat also changed, and as a result, the shape and location of the new patches changed.

Discussion

The small patches' capacity in supplying pollination

Our results showed that the effects of forest fragmentation on pollination were influenced by two main factors: 1- the small patches' capacity in supplying pollination and 2-The proportion of the landscape occupied by forest patches or simply habitat amount. In general, when the small patches' capacity in providing pollination was insignificant, fragmentation increased pollination. As the capacity increased, landscapes with a fragmented pattern of forest patches indicated higher levels of pollination. The combined effects of P and the habitat amount altered the position of maximum pollination on the graph. Mitchell et al. (2015) found that increasing the small patches' capacity to supply ecosystem services changed the position of maximum services (peaks). With increasing this capacity, the peaks occurred at high ranges of habitat amount. It is noteworthy that Mitchell et al. (2015) merely examined the effects of habitat loss on distance-dependent services such as pollination, and did not evaluate the effects of fragmentation on ecosystem services.

Increasing values of P in Equation 1 imply that small patches could have an equal capacity in providing pollinating to large patches. In this regard, the patches' capacity in supplying pollination was set between 0 and 1, which indicated the maximum capacity by 1. For example, at p = 0.001, a patch containing 2300 cells had a capacity of 0.9 in providing pollination, while at p = 0.008, this capacity occurred for a patch with 300 cells. Such patches in the simulated landscapes in the present study constituted 0.12% of the entire landscape. As the value of P increased, the capacity of small patches equaled extensive patches, which was almost unexpected. For example, at p = 0.16, the patches including 15 cells had a capacity of 0.90, and a patch with 90 cells had the maximum capacity (one) to provide pollination to the surrounding environment. Therefore, the type of relationship that determined the patches' capacity in supplying pollination had a significant effect on the results. Empirical studies have shown that large patches provide more services than small patches (Tscharntke and Brandl, 2004), but the ratio is unclear and needs to be addressed in further studies. However, Small forest patches in the agricultural landscapes can accommodate diverse communities of pollinators (Proesmans et al., 2019) and the effect of these patches is local. Proesmans et al. (2019) found that small forest patches positively affected pollination In a radius of 100 meters. Therefore, even small, scattered patches can increase pollination locally.

Habitat amount has also been reported as a significant factor affecting the relationship between fragmentation and pollination. For example, high habitat amounts in a landscape result in species spillover from these natural habitats to the surrounding fields (Kammerer et al., 2016). When the habitat amount in a landscape is low, fragmentation forced pollinators to devote more energy to foraging (Maurer et al., 2020). Maurer et al. (2020) reported the adverse effects of fragmentation on bumblebee colony size at low habitat amounts and a positive effect at high habitat proportions. In contrast, landscapes with high amounts of habitat and a low degree of fragmentation have shown higher pollinator visitation (Schüepp et al., 2014). Everaars et al. (2018) found that the higher ratios of nesting habitat to foraging habitat resulted in the higher visiting rate in foraging habitat because fragmentation increased accessibility to nesting habitat. Maurer et al. (2020) argued that fragmentation could not be considered as a useful or adverse process because fragmentation was strongly dependent on habitat amount in the landscapes. The mentioned study showed that increasing habitat amount along with increasing fragmentation increased pollination. However, in our study, this result was obtained only when the capacity of small patches to supply pollination was high. (i.e., $P > 0.08$). In landscapes that small patches had low capacity in comparison to large patches (for example, $P=0.001$), we found that fragmentation effects were not dependent on habitat amount, and in all proportions, fragmentation negatively affected pollination. However, as the capacity of small patches increased, habitat amount became an affecting factor and changed that the effects of fragmentation on pollination especially in proportions less than 0.2. Therefore, fragmentation can have both positive and negative effects on pollination (Fahrig, 2017), according to the capacity of small patches in supplying pollination.

Importance of landscape metrics

Estimating the relationship between different aspects of landscape structure patterns and ecosystem services such as pollination is unfruitful without using landscape metrics. There are more than one hundred metrics in Fragstats software (McGarigal et al., 2002) to measure various aspects of features within a landscape. Still, most studies have used a small number of simple metrics such as distance from patches and area of the patch for estimating the relationship between landscape structure and pollination.

Landscape metrics also showed variability and unpredictability of the effects of fragmentation on pollination. For example, our results showed that at P less than 0.008, pollination decreased with an increasing number of patches (NP), but Joshi et al. (2016) showed that the number of patches increased pollination. This result achieved on a small scale (less than 500 m) that the number of patches increased the number of bees, which was due to more habitat and floral resources for the bees. They concluded that more patches provide more nests (Joshi et al., 2016). Our results showed that an increase in the number of patches increased pollination only at P greater than 0.08 and only at habitat amounts greater than 0.3.

The increase in the average patch size (AREA-MN) in our study resulted in an increase in pollination that was consistent with the results of Joshi et al. (2016). Saturni et al. (2016) showed that forest cover had a positive effect on the diversity and abundance of bees. With the increasing forest patches area, the diversity and abundance of bees also increased. They also showed that these effects varied at different scales, and bees on a small scale were inversely related to the forest patches size (Saturni et al., 2016). One reason is that in a landscape, only patches larger than a certain area can supply significant services to the surrounding environment. For coffee plants, for example, forest patches having an area of 60 hectares, were large enough to support a diverse population of pollinators to pollinate located fields (Ricketts et al., 2006). However, some studies have shown that orchid habitats with an area of fewer than 385 hectares are too small to maintain a population of pollinators (Pauw, 2007). In the present study, with increasing small patches' capacity, AREA-MN showed a negative correlation with pollination.

In the present study, we used the average distance between patches (ENN-MN) metric to measure the connectivity of patches. Fragmentation leads to an increase in this metric because patches are scattered around the landscape, and as a result, the distance between these patches is increased. Our results showed that when small patches had minimal capacity to supply services, connectivity decreased pollination. Farwig et al. (2009) also showed that pollination was inversely related to the isolation of forest patches, and the fragmented pattern of forest patches reduced the pollination rate. Boreux et al. (2013) also showed that the bees' abundance decreased with increasing distance from the nearest forest patches. In contrast, Mitchell et al. (2013) examined 69 articles related to the effects of connectivity on ecosystem services in detail. They found that 74% of these articles showed that connectivity increased pollination. Isolation native patches have a significant effect on the pollinators' activity and abundance. For crops such as coffee and watermelon, pollinators' abundance and visiting rates were less observed in highly isolated areas (Ricketts et al., 2006). For coffee plants, Bravo-Monroy et al. (2015), at distances of 0 to 800 meters from forest patches, showed that proximity to the forest increases the abundance of bees. De Marco and Coelho (2004), at distances below 1 kilometer showed that fields near forest patches had a 14% increase in yield, which was related to pollination. Ricketts et al. (2004) and Ricketts et al. (2006) found that bee diversity, visiting rate, and pollen accumulation rates were significantly higher in coffee fields near forest patches than in those farther away.

The complexity of the patches also had significant effects on pollination. To measure the shape and complexity of the patches, we used two metrics PAFRAC and ED. These metrics had different impacts on pollination in different proportions and P. High values of PAFRAC, and ED imply that the patches' shape becomes more complex. Our results showed that when small patches had a little impact on the service provision, increasing edge density and shape complexity affected pollination negatively. Still, when the impact increased, shape complexity increased pollination, which was more notable in proportions greater than 30% of the total landscape. Increasing patches' edge reduces accessibility to food and increases predators' presence (Betts et al., 2006). Small bees are sensitive to the edges and change their behavior due to the presence of predators (Hadley and Betts, 2012). Reducing landscape complexity and increasing isolation also minimizes pollinators' diversity (Ferreira et al., 2013). Hass et al. (2018) found that landscapes with high edge densities of farms maintained more bees. The decreased visiting rate of bees with decreasing complexity on a small spatial scale has also been shown (Breitbach et al., 2012), although there was a very weak statistical relationship.

The effect of spatial scale in creating new patches to increase pollination

In this part of the present study, the most significant result was the effect of the spatial extent on the created patches' location that emphasizes the importance of investigating the effect of scale in ecological studies and pollination. The effect of spatial scale on pollinator activity has been practically studied in several studies, and it has often been stated that the pollinator population decreases with increasing spatial scale. For example, on a large scale (more than 500m) in heterogeneous landscapes, resources are redundant and have marginal effects on pollinators, as bees meet their needs without having to move over this distance (Joshi et al., 2016). In landscapes with low heterogeneity, bees have to travel longer distances.

The presence of additional habitats in a radius of 1750 meters reduces the abundance of pollinators in small patches (Grass et al., 2018), probably because they leave small patches and move to larger patches with better food. Saturni et al. (2016) found that large bees were affected on a large scale and small bees on a small scale. Joshi et al. (2016) also showed that the effects of landscape configuration on bee visiting rate on small scales were more detectable for apple orchards. Optimal foraging theory also states that in a landscape, with uniform distribution of resource patches, bees travel near their nesting areas to reduce energy and time consumption and increase foraging efficiency (Heinrich, 2004). Therefore, if the patches created to increase the pollination level are far away from the floral resources, they will not be useful. It can be concluded that the new patches should be scattered around the floral resources to reduce energy consumption, according to the theory. It is noteworthy that the creation of artificial nesting resources requires an examination of the situation before and after the creating of these patches for at least one year because it is difficult to identify whether the population of pollinators has increased (Dainese et al., 2018).

Conclusion

The main purpose of the present study was to determine an optimized pattern of forest patches providing the highest pollination level in an agricultural landscape. The most crucial conclusion obtained from the present study was that the effects of fragmentation on pollination were mainly dependent on the capacity of small patches in supplying pollination. Habitat amount was another factor that changed the effects of fragmentation on pollination in some cases. Therefore, the pattern of forest patches providing the maximum level of pollination changed according to the mentioned factors. This reason made it impossible to determine a specific pattern of forest patches to achieve the maximum possible pollination rate in an agricultural landscape. We showed that in creating new nesting habitats, special attention should be paid to the issue of spatial scale. After evaluating the relationship between landscape patterns and pollination, we can increase pollination in a landscape by creating new forest patches. Therefore, future studies should pay more attention to this issue and identify the factors affecting pollination in the landscape. In this study, only the behavior of bees was examined that were compatible with the exponential model, and it is necessary to investigate the results of other statistical models in this field. For any landscape, we first recommend studying the behavior of pollinators and their ability to forage and then act to create new patches according to the model and statistical relationship between landscape structure and pollination. The patches' capacity to supply pollination is also not well studied and it is suggested that more studies be done in this field and to determine the minimum habitat required for pollinating species. Ecosystem management that seeks to maximize an ecosystem service often leads to a significant reduction in the provision of other ecosystem services (Bennett et al., 2009). As a result, there is often a trade-off between agricultural production and environmental protection (Pilgrim et al., 2010). Therefore, we recommend considering the trade-off between ecosystem services in the landscapes that increasing pollination results in a reduction in other services.

Abbreviations

NP: Number of Patches; ENN-MN: Mean Euclidean Nearest-Neighbor Distance; Area_MN: Mean Patch Area; ED: Edge Density; PAFRAC: Perimeter-Area Fractal Dimension; AI: Aggregation Index;

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and material

Data are available on request from the authors only based on logical requests.

Code availability

Code available on request from the authors only based on logical requests.

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Authors' contributions

Ehsan Rahimi has written the paper and has done the modeling part of the analysis.

Shahindokht Barghjelveh has reviewed the paper, helped to write, and interpreted the results.

Pinliang Dong has reviewed the paper, edited grammar, and helped to respond to the paper's questions.

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Figures

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Figure 1

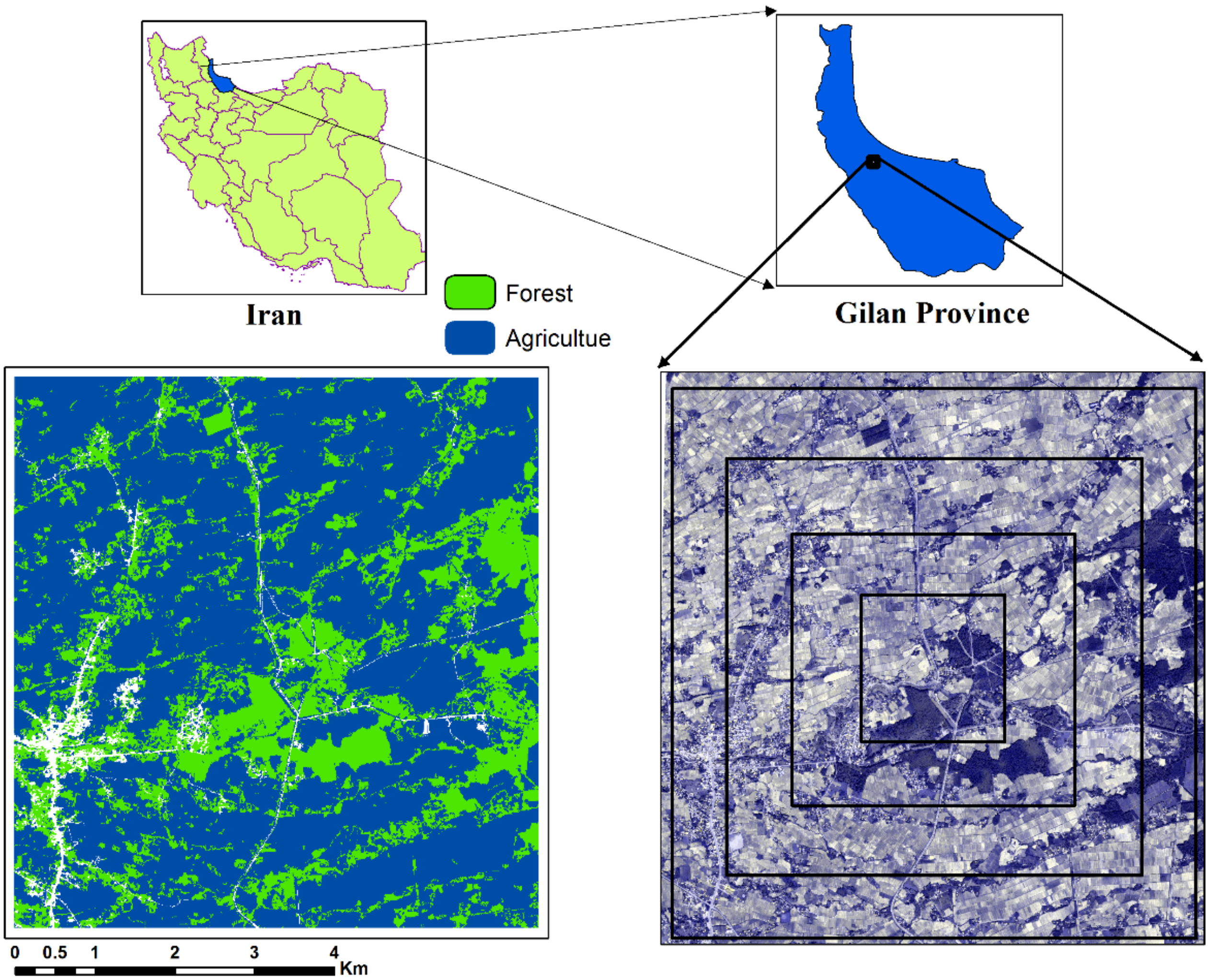

Figure 2

Location of the study area in Iran and Gilan province. The image on the right shows an aerial photo of the study area, and four subsets for creating new patches have been drawn by black lines at four different spatial scales.

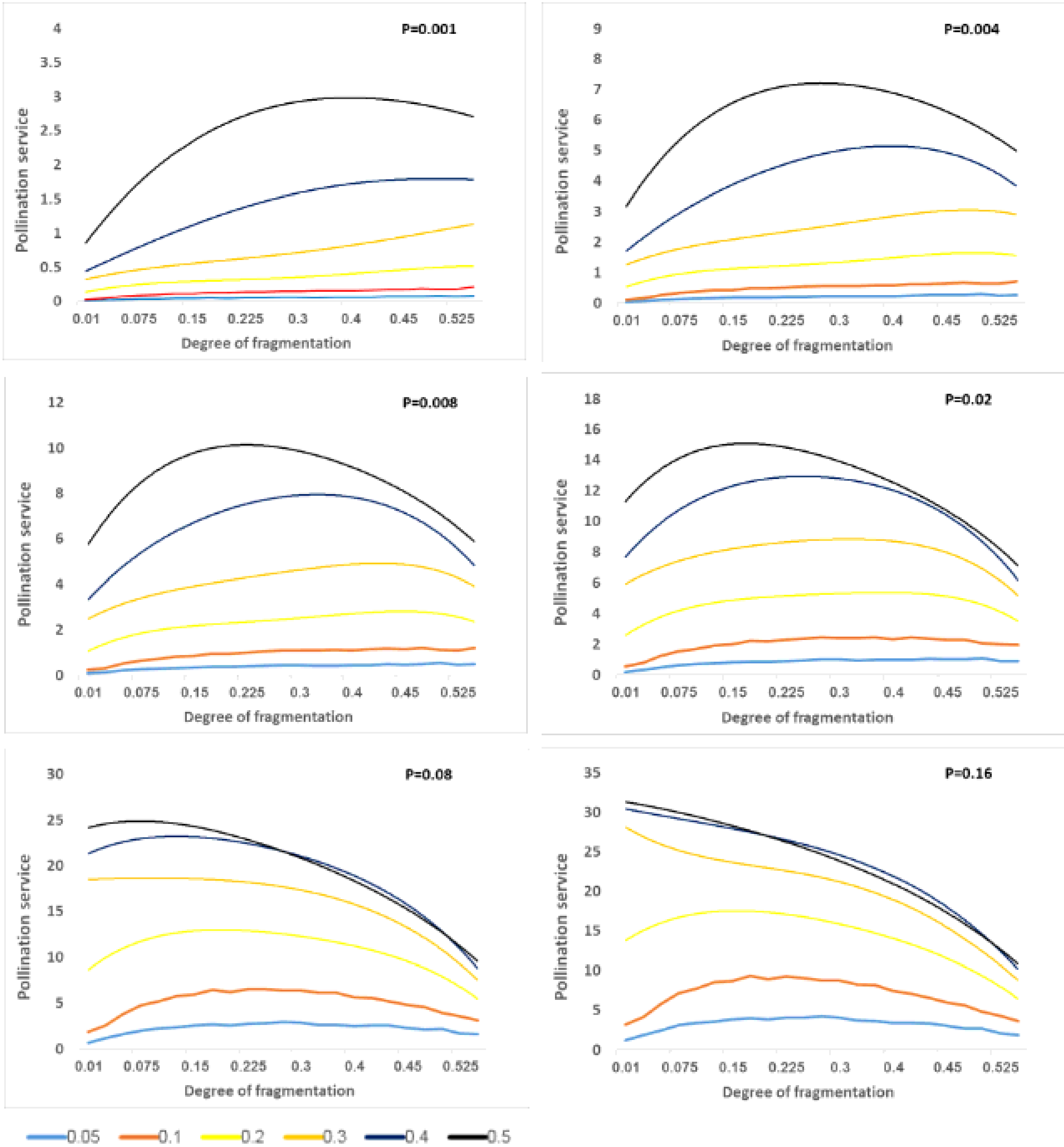

Figure 3

Pollination shifts according to forest fragmentation level, and small patches' capacity in supplying pollination. The shift of the maximum pollination level from P = 0.001 to P = 0.16 is obvious.

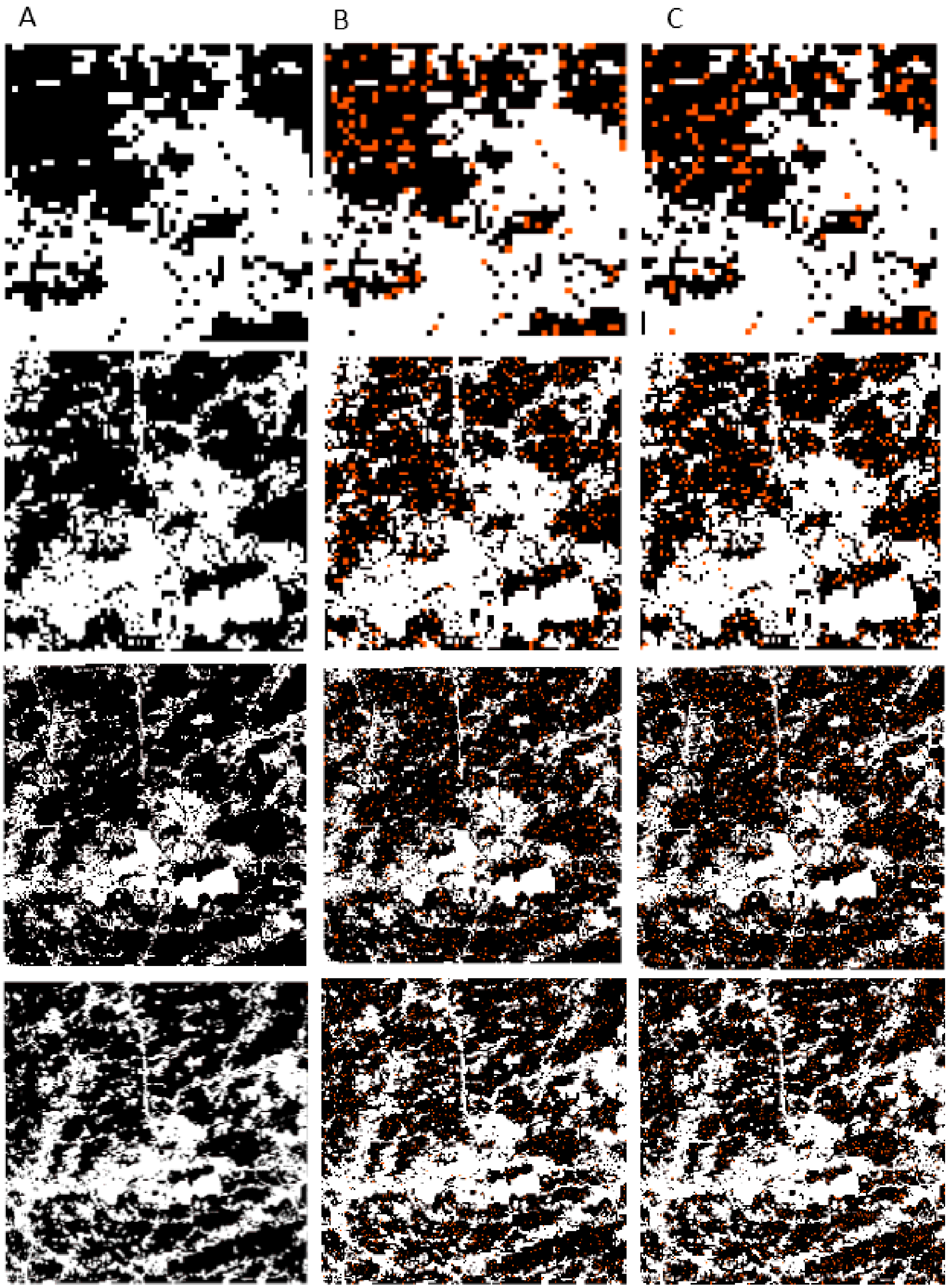

Figure 4

Generated patches by genetic algorithm for different P in four subsets of the study area. Column (A) shows the original landscapes, and column (B) shows the patches' position created for P = 0.001, and column (C) shows the patches created for P = 0.16. New patches are colored in orange.