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Risk factors and strategies for integrated management of bird pests affecting maize establishment

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ABSTRACT

Bird damage to maize crops is an important cause of economic loss for maize growers in Italy. Consequently, the objectives of this study were to identify main species of birds attacking maize in north-eastern Italy and quantify the effects of agronomic characteristics, cultivation practices, landscape variables, and management practices on the incidence of bird damage to maize at establishment. A systematic survey of 5065 ha of maize cultivated land (*Zea mays* L.) at early plant stages was performed from 1986 to 2020, resulting in a dataset of 1619 records. Corvids (*Corvus cornix*) were found to be the main culprits of damage to maize fields. A multifactorial model was applied to assess the impact of potential risk factors. The presence of nearby roosting areas, such as hedgerows and woodlands with trees higher than 7 m, was associated with a five-fold increased risk of damage by birds. No-tillage soil management was associated with a higher risk of bird damage when compared with minimum tillage and conventional tillage systems. The probability of damage to a field with no risk factors was always low (<1%). The application of naturally derived bird repellents incorporated in seed coatings (i.e., ScudoSeed® and Eurodif®) decreased the risk of damage to maize by birds below the threshold value of 15%, yet they were slightly outperformed by their synthetic counterparts (i.e., Methiocarb and Ziram). Our results further suggest that it is possible to implement IPM principles for pest birds in maize.

1. Introduction

Crop emergence may often fail under field conditions, yet very little quantitative information is available in the literature on the economic impact, precise cause/s, or the ranking of factors associated with this failure (Lamichhane et al., 2018). This informational gap includes bird damage to agricultural crops (Giunchi et al., 2012) as an important cause of economic loss for farmers worldwide (e.g., maize [DeGrazio, 1978; Canavelli et al., 2014; Khan et al., 2015; Wise, 2018]; rice [Gebhardt et al., 2011]; cereals [Coleman and Spurr, 2001; Khan et al., 2015]; sunflower [Canavelli et al., 2014]; and soybean [Nasu and Matsuda, 1976; Firake et al., 2016; Lamichhane, 2021]). Nevertheless, only a few studies have assessed the intensity of maize seed and seedling damage by birds that occurred before the crop-establishment phase (Khan et al., 2015; Wise, 2018).

A wide variety of bird species can cause damage to many agricultural crops (DeGrazio, 1978; Soldatini et al., 2006; Canavelli et al., 2014; Gebhardt et al., 2011), and most currently used methods for reducing this damage are unsatisfactory. The primary maize-damaging taxa in northern Italy are corvids, such as hooded crows (*Corvus cornix*) and magpies (*Pica pica*) (Rolando et al., 1998; Nicoloso et al., 2015). These eclectic and omnivorous species can adapt to a variety of environmental resources and have now become very common in agricultural and natural habitats, as well as in residential areas. Other species with an occasional local impact include semi-domestic pigeons (*Columba livia* var. *domestica*), wood pigeons (*Columba palumbus*), pheasants (*Phasianus colchicus*), greylag geese (*Anser anser*), wild ducks (*Anas* spp.), and gulls (Nicoloso et al., 2015). Because most of these maize damaging bird species move over large areas, their abundance and foraging distribution early in the growing season, and consequently damage to maize crops at establishment may be affected by the quality of food within foraging fields, environmental characteristics, habitat composition surrounding maize fields, and management practices (Canavelli et al., 2014).

Recent interest has focused on the use of repellents to protect crops

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from depredating birds (Lentola et al., 2020). The effectiveness of repellents is, however, influenced by the physiology and behaviour of the pest bird, its hunger and social interactions, the characteristics of the crop to be protected (Crabb, 1985; Esther et al., 2013), and repellents are not always the solution to bird problems. Furthermore, there are general concerns over the unwanted environmental effects of synthetic chemical repellents to reduce the incidence of bird damage (e.g., the amount of chemical residues remaining on the crop at harvest, impacts on non-target animals, and adverse effects on the growth and development of the crop (Lentola et al., 2020). The addition of alternative management strategies would reduce the frequency of repellent applications necessary to attain adequate control.

Consequently, maize-damaging birds should be controlled within the framework of integrated pest management (IPM) principles (Barzman et al., 2015), which have been considered for a specific legislation in Europe (Directive, 2009/128/EC). The first IPM step involves prevention i.e., the implementation of a series of measures, such as crop rotation, that will create conditions that reduce the frequency and intensity of pest outbreaks and thus the need for plant-protection measures. Once these conditions have been created, the subsequent IPM procedure to decide action can be summarized in two fundamental steps. Before any decision on pest control is taken, harmful organisms must be monitored with adequate methods and tools, where available; tools should include observations in the field as well as scientifically sound warning, forecasting and early diagnosis systems. In this way treatments can be applied only in those situations where economic thresholds are exceeded. When economic thresholds are exceeded, agronomic strategies, biological control, physical treatments, and other non-chemical pest control methods should be considered as a replacement for synthetic chemical treatments. When no alternative pest control methods are available, synthetic chemical treatments should be selected from options that pose the lowest risk to the environment and human health (Lentola et al., 2020). They should be used cautiously and deliberately, not indiscriminately, to minimize selection pressures on pest populations.

Consequently, the objectives of this study were to: (1) identify main species of birds attacking maize in north-eastern Italy and evaluate the main structural strategies (long-term agronomical practices) to reduce their impact on crops; (2) quantify real incidence of bird damage and the incidence of various other potential risk factors; and (3) test low-impact solutions for crop protection (i.e., naturally derived repellents combined with an insurance approach) as an alternative to regulated synthetic chemical repellents as seed coatings; an approach that patently contrasts with the fundamental principles of IPM.

2. Materials and methods

An extensive survey of 5065 ha of maize fields was conducted in the northeast of Italy (area covered: 45.64 N, 12.96 E and 45.05 N, 11.88 E) from 1986 to 2020 (35 consecutive years of observations), resulting in a dataset of 1619 records (Table 1). The average surveyed area was 145 ha per year with a standard deviation (SD) of 90. The minimum surveyed area was 11 ha in 1989 and the maximum surveyed area was 411 ha in 2014. Therefore, the survey comprised a random sample of maize fields in terms of size of an area that was investigated.

Surveyed fields represented a balanced sample of agronomic conditions in northeast Italy. The data were either collected directly from at least three inspections per field each year or obtained from official regional databanks (see below). The dataset included untreated (no bird repellent-coated seeds, 98% of the total surface) and treated fields. Cultivated land treated with repellent-coated seeds accounted for 2% of the total (37% in the last two years of observations).

Table 1
List of the variables included in the database.

Variables	Explanation	Type	Classification	Maize cultivated land (ha)	% on total Maize cultivated land
Year	Year of data collection	Ordinal	≤1990	393	7.76
			1991–1995	415	8.19
			1996–2000	583	11.51
			2001–2005	550	10.86
			2006–2010	844	16.68
			2011–2015	1370	27.09
			2016–2020	909	17.95
			Total	5065	100
Crop damage	Damage index: percentage of total plant damaged by birds	Quantitative	0–5.00	4971	98.14
			5.01–15.00	75	1.48
			15.01–50.00	7	0.14
			50.01–80.00	9	0.18
			≥80.01	3	0.06
	Re-sowing	Qualitative	Yes	12	0.24
			No	5053	99.76
Birds	Main bird species recorded	Qualitative	Corvid	5061	99.92
			Greylag geese	2	0.04
			Wild ducks	2	0.04
Soil properties	Texture	Qualitative	Heavy soils	4044	79.84
			Light soils	86	1.70
			Loam soils	796	15.72
			NA	139	2.74
Agronomic practices	Tillage	Qualitative	Conventional (CT)	4971	98.15
			Minimum Tillage (MT)	77	1.52
			No Tillage (Sod Seeding)	17	0.34
	Repellents	Qualitative	No (no bird repellent-coated seed)	4952	97.77
			Yes (any type of seed coatings)	113	2.23
Vegetation	Roosting areas within 300 m	Qualitative	No	4537	89.58
			Yes	458	9.04
			NA	70	1.38

NA = Not Assessed.

2.1. Soil properties

The soil texture data were obtained from the Veneto Region Environmental Protection Agency (ARPAV) data bank (ARPAV, 2015). Soil from each surveyed field was classified based on soil texture, according to the soil characteristics of its soil map units (SMU; see ARPAV [2015] for more details). The textures of the soils were determined using the United States Department of Agriculture (USDA) triangle method (USDA, 2014) based on analyses conducted with a sedimentation pipette. Sandy loam and loamy sand soils were classified as "light soils"; loam and sandy clay loam were classified as "loam soils"; and silty clay loam, silt loam, clay and clay loam soils were classified as "heavy soils". No stony soils were found in the study areas.

2.2. Agronomic practices

Land management practices were similar across all study locations and included: fertilization with 240–300 N kg, 70,000 to 80,000 seeds/ha, inter-row width 75 cm, plus pre-emergence and post-emergence herbicide treatments causing very low weed densities. Seeding depth varied across study sites from 2.5 to 9 cm (dry seed bed). The following commercial maize hybrids were used:

Anita, Costanza, Alicia, Senegal (1993–2001); Tevere (2002–2004); DKC6530 (2005–2006); DKC6530, Mitic, Kermess, Klaxon (2007–2008); DKC6666, NK Famoso, PR31A34, and PR32G44 (2009–2010); and DKC6677, PR32G44, and NK Famoso (2011); Korimbos, Kalipso and P1547 (2012–2014); Kontigos, P1028, P1547, DKC5830, (2015–2019), P1028, PR32B10, Kefrancos (2020).

The majority of the surveyed fields (~4971 ha) were conventionally tilled (i.e., ploughing, cultivator passages, harrowing, and hoeing), followed by approximately 77 ha of fields under minimum tillage (i.e., one cultivator passage, harrowing and hoeing), and around 17 ha (0.3%) of fields under no tillage (sod-seeding).

2.3. Roosting areas

The effect of surrounding roosting areas within 300 m of the surveyed fields on the incidence of bird damage to early growth stages of maize was also analysed. More specifically, only nearby hedgerows and woodland areas with trees over 7 m tall (no more than 10 m apart) were considered as roosting areas. The primary arboreal plants (the tallest ones) were *Fraxinus excelsior, Quercus robur, Salix alba, Fraxinus oxycarpa, Carpinus betulus, Populus alba, Ulmus minor, Acer campestre, Populus nigra, Fraxinus ornus,* and *Salix caprea*; shrubs were represented by *Sambucus nigra, Crataegus monogyna, Corylus avellana, Prunus spinosa, Cornus mas, Cornus sanguinea,* and *Evonymus europaeus*. The primary hedgerow plants were *Populus alba, Ulmus minor, Fraxinus oxycarpa, Quercus robur, Quercus pubescens, Carpinus orientalis,* and *Carpinus betulus*. Secondary hedgerow plants were shorter than primary trees, yet they usually exceeded 7 m in height; these trees grow among the primary arboreal species. The five most dominant secondary hedgerow species included *Acer campestre, Salix alba, Platanus hispanica, Carpinus orientalis*, and *Fraxinus ornus*. The shrub outfit was represented by a few alternate species i.e., *Viburnum opulus, Cornus sanguinea, Crataegus monogyna,* and *Prunus spinosa*.

2.4. Bird repellents

The effect of four candidate repellents on damage to maize by birds was assessed relative to untreated fields. These treatments included: 1) untreated controls (maize seeds treated with 1 L/t seed fungicide Celest® [a.i., metalaxil + fludioxonil]; used in all surveyed fields; 2) Mesurol® (maize seeds coated with 1 L/t seed fungicide Celest® [a.i., metalaxil + fludioxonil]and 1 L/100 kg seed Mesurol 500 FS® [a.i., methiocarb carbamate]; 3) Korit® (maize seeds coated with 1 L/t seed fungicide Celest® [a.i., metalaxil + fludioxonil]and Korit 420 FS®, containing 420 g/L of ziram at a dose of 87.5 mL/50,000 maize kernels; 4) ScudoSeed® (maize seeds coated with 1 L/t seed fungicide Celest® [a.i., metalaxil + fludioxonil]and 1 kg/100 kg seed ScudoSeed® [consisted of 0.2% organic carbon extracted from seaweeds and 0.7 g/L of mannitol]); and 5) Eurodif® (maize seeds coated with 1 L/t seed fungicide Celest® [a.i., metalaxil + fludioxonil] and 1 kg/100 kg seed Eurodif® [olfactory repellent powder based on aluminium and ammonium sulphate added in the seed-coating phase]).

2.5. Identification of harmful species and damage assessment

It was difficult to identify the bird species causing maize damage during establishment phase, as they did not always leave clear footprints on the ground, and traces of seed removal could not be used to identify bird species causing damage to maize. In most of the fields (i.e., 60% of surveyed locations), identification of bird species damaging maize to maize at establishment was based on direct and occasional observations of birds feeding on maize rows during field inspections.

At the 2nd and 3rd and 6th through 8th leaf stages of the maize plants, two sub-plots of 20 m × 4 rows of maize per field or portion of field were chosen at random after a first general field homogeneity assessment; in cases when areas had evidently different conditions because of crop density or development, fields were divided into sub-areas; each sub-area was assessed by identifying at least two sub-plots and considered as a specific record in the database. The causes of damage to seeds, seedlings and small plants within each row were identified. Additionally, soil within 10 cm diameter around affected or missing plants was excavated up to a depth of 5–10 cm in search of possible pest damage to seeds and/or emerging seedlings.

The following parameters were evaluated: 1) number of normal plants (no symptoms); 2) number of failures by birds (e.g., seeds missing due to typical feeding activity by birds leaving a conical hole in the ground); 3) number of missing plants uprooted by birds looking for seed below (e.g., the uprooted plant was usually found near the hole in the row); 4) number of failures from other causes (e.g., non-germinated seeds, predation by other vertebrate pests - e.g., feral hogs, mice); and 5) number of plants with insect-damage symptoms (e.g., wilting of central leaves, broken central leaf due to holes in the collar, wilting of whole small plants). Total damage by birds was calculated as the sum of damaged emerged plants and seeds divided by the total number of planted seeds. The average total damage of rows assessed in a field/sub-area was added to the database alongside field characteristics.

2.6. Statistical analysis

Analysis was performed by SAS 9.4 (Institute Inc., Cary, NC). All of the statistical models used the observed land surface area as a weight variable. A logistic regression was performed to estimate the probability of re-sowing based on the percentage of damaged plants (Lambert and Lipkovich 2008). The mean probability, standard deviation, plus minimum and maximum values, were calculated by class of damaged plants. Due to the non-normal distribution of the data, the percentage of damaged plants was analysed by using a generalised linear model assuming a Poisson distribution (PROC GENMOD). The following fixed effects were included in the model as predictors (Table 1): years, presence of roosting areas, soil texture, treatments, and agronomical practices. The estimated least-squares means were calculated with 95% confidence intervals (95% CI). Post-hoc pairwise comparisons among levels of factors were performed by using Bonferroni correction. This approach enables an estimate of the relative risk (RR) of increase in the percentage of damaged plants due to the different levels of the fixed factors included in the model (Zou, 2004).

3. Results

3.1. Identification of harmful bird species

The two most dominant bird species observed damaging maize fields were hooded crows and magpies, which accounted for over 99% of all birds that were observed feeding on the crop rows. Mallards and greylag geese were found to cause conspicuous damage to maize, but infrequently (Table 1), with only seven out of 1619 detection records (0.04% of the total considered surface for each species) and the average percentage of damaged plants of 53%. The damage caused by pheasants, semi-domestic pigeons and wood pigeons was minor while the presence of gulls was even more sporadic. Very few cases of maize damaged by Anatidae were associated with flooded maize fields as it was possible to observe the damaging birds under these conditions.

3.2. Risk factors

During the 35-year monitoring period, bird attacks were mostly on well below 15% of the seeds sown, the indifference threshold below which there are no significant effects on maize production in terms of quantity and quality of plants (Furlan et al., 2017). The total cultivated land damaged by birds to an extent likely to cause economic damage (>15% of sown seeds) was 0.36% of the total observed land, or 0.29% of the untreated cultivated land. In most cases, damage was certain (0.22% of the untreated cultivated land, Table 2) and represented by re-seeding costs (roughly 250 euro/ha) and yield reduction due to delayed sowing (highly variable in terms of sowing delay in days, hybrid type, and soil/climate conditions). The damage attributable to birds was observed both before seedling emergence and in the 1st–3rd leaf stage, during which birds damaged maize by pulling seedlings/young plants out of the soil to eat the seed, resulting in plant death. Soil-moisture conditions seemed to be the main driver of damage period since birds did not search for seeds when the soil was wet. When the soil is initially wet, bird-seed predation may become more concentrated after plant emergence due to dryer soil conditions, and vice-versa.

Considering corvids alone, plant damage showed conspicuous variations over the years (Fig. 1), with a significant increase over the last five-years period ($P < 0.001$). The main risk factor for bird damage was the presence of roosting areas within 300 m of the fields (Fig. 2a). This factor increased damage risk almost five-fold (RR = 5.3; 95% CI 4.8–5.8, $P < 0.001$). Tillage significantly affected bird-damage risk, as well (Fig. 2a). No-tillage conditions increased bird-damage risk about four-fold when compared with conventional tillage (RR 3.73; 95%, CI 2.8–5.0; $P < 0.001$). Since seeds were coated with repellents in only 10% of conventional tillage cases, compared with 28% of no-till cases, this risk increase appears particularly significant. Furthermore, no-tillage conditions increased bird-damage risk eleven-fold when compared with minimum tillage (RR = 11.3; 95% CI 8.0–16.0; $P < 0.001$), but in 57% of minimum tillage cases, seeds were repellent-treated. As for soil texture, loamy soils increased damage risk by 50% when compared with heavy soils (RR = 1.5, 95% CI 1.4–1.7, $P < 0.001$) and by 40% when compared to light soils (RR = 1.4; 95% CI 1.1–1.8, $P < 0.001$).

Considering the 2019–2020 period (270 records), when all the repellent substances were used and compared, and bird pressure was higher, the application of the repellent substances as seed coatings reduced bird damage by 40% (RR = 0.6; 95% CI 0.5–0.7; $P < 0.001$). There was a significant interaction between the presence of roosting areas and repellent seed-coatings (Fig. 2b); where no roosting areas were present, repellent seed-coating did not significantly reduce damage, with the damage level being very low (about 1% of damaged plants on average). However, when roosting areas within 300 m were present, the damage level was higher (7% of damaged plants on average), with repellent seed-coatings reducing damage risk by 80% (RR = 0.2; 95% CI 0.2–0.3; $P < 0.001$). When the individual repellent substances under study in 2019–2020 were compared, major differences were found (Fig. 2c). Regulated synthetic chemical repellents (Mesurol® and Korit®) reduced bird damage significantly more than the two naturally derived repellents (Eurodif® and ScudoSeed®). The first type of repellents reduced bird-damage risk by 95% when compared with untreated fields (RR = 0.05; 95% CI 0.04–0.08; $P < 0.001$), whereas ScudoSeed® and Eurodif® reduced bird-damage risk by 70% when compared with untreated fields (i.e., planted with uncoated seeds): RR = 0.28; 95% CI 0.23–0.34; $P < 0.001$ and RR = 0.21; 95% CI 0.16–0.26; $P < 0.001$, respectively. Nevertheless, ScudoSeed® and Eurodif® treatments always kept damage levels below 15% of the sown seeds, with the exception of two cases out of 81 (18.7% and 22.3%); the two regulated synthetic chemical treatments performed similarly, with the threshold being exceeded in two cases out of 78 (18.7% and 29.1%); thus, it seems that the two biologically based repellents are somewhat effective for reducing economic damage risk by bird attacks, as well as being a reliable alternative to synthetic chemical pesticides.

4. Discussion

Our long-term 35-year study showed that the economic damage to maize by birds in north-eastern Italy was generally low (<1%, or about 4% associated with the presence of nearby roosting areas), yet this can still result in limited re-seeding (0.22%) of affected fields. Significant variations in levels of bird-damage were observed among study years. This is presumably due to the bird feeding habits as corvids are omnivores, they do not seem to show a particular preference for a single food source, but rather can adapt to local environmental conditions and to temporary food-supply situations, eating seeds of various crops, sprouts, waste, plant residues, small animals, carcasses, and anything that they consider edible. If corvids are attracted to another temporary food resource during periods of the first maize leaves, damage may be irrelevant. However, when no other alternatives are available to them, corvids may turn their sole attention to maize.

Our results indicated an increase in bird damage to maize over the past five years, exceeding a total of 1%. During this period, the number of nearby roosting areas has increased notably as a result of the implementation of European and Regional directives to increased biodiversity of cultivated lands, which might be an explanation for such changes. Indeed, in our study the higher risk of corvid damage to maize was associated with: 1) the presence of hedgerows and woods with tall trees (over 7 m) bordering cultivated plots; these areas provide suitable habitats for birds' rest, reproduction and roosting; and 2) no-tillage

Table 2
Probability of bird damage causing maize resowing according to the main damage classes (untreated fields).

					Re-sowing probability			
Damage class	Records	Maize-cultivated land (ha)	Re-sown fields	Maize- cultivated land re-sown (ha)	Mean	SD	Minimum	Maximum
≤5%	1334	4865	0		<0.001	<0.001	<0.001	<0.001
5–15%	32	72	0		0.001	<0.001	<0.001	0.003
15–50%	9	4	3	3	0.090	0.187	0.004	0.587
50–80%	13	8	9	6	0.855	0.131	0.649	0.991
>80%	3	2	2	2	0.998	<0.001	0.997	0.999
Total	1391	4952	14	11				

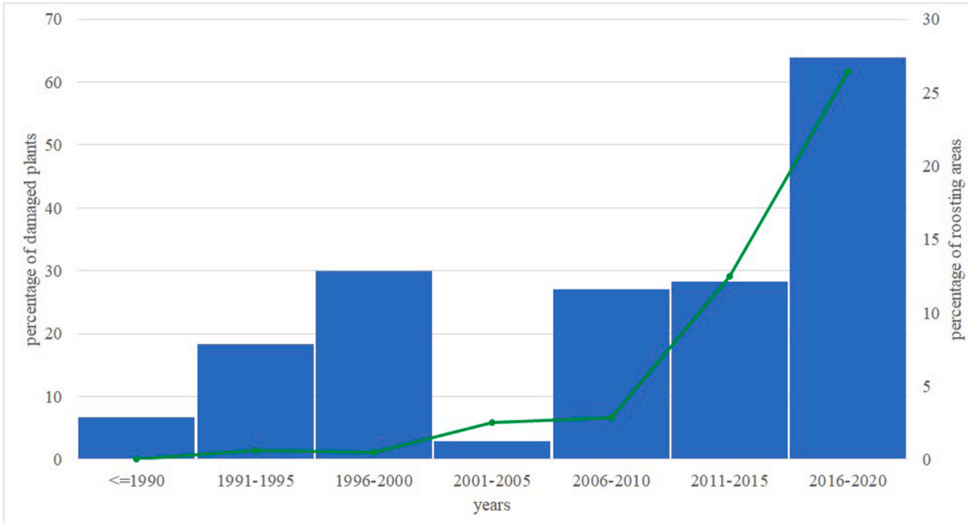

Fig. 1. Patterns of bird plant damage and percentage of roosting areas over the years. Least-square means of percentage of damaged plant for each five-year period were reported (histograms). Percentage of observed roosting areas (line) on the total recorded surface was represented. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

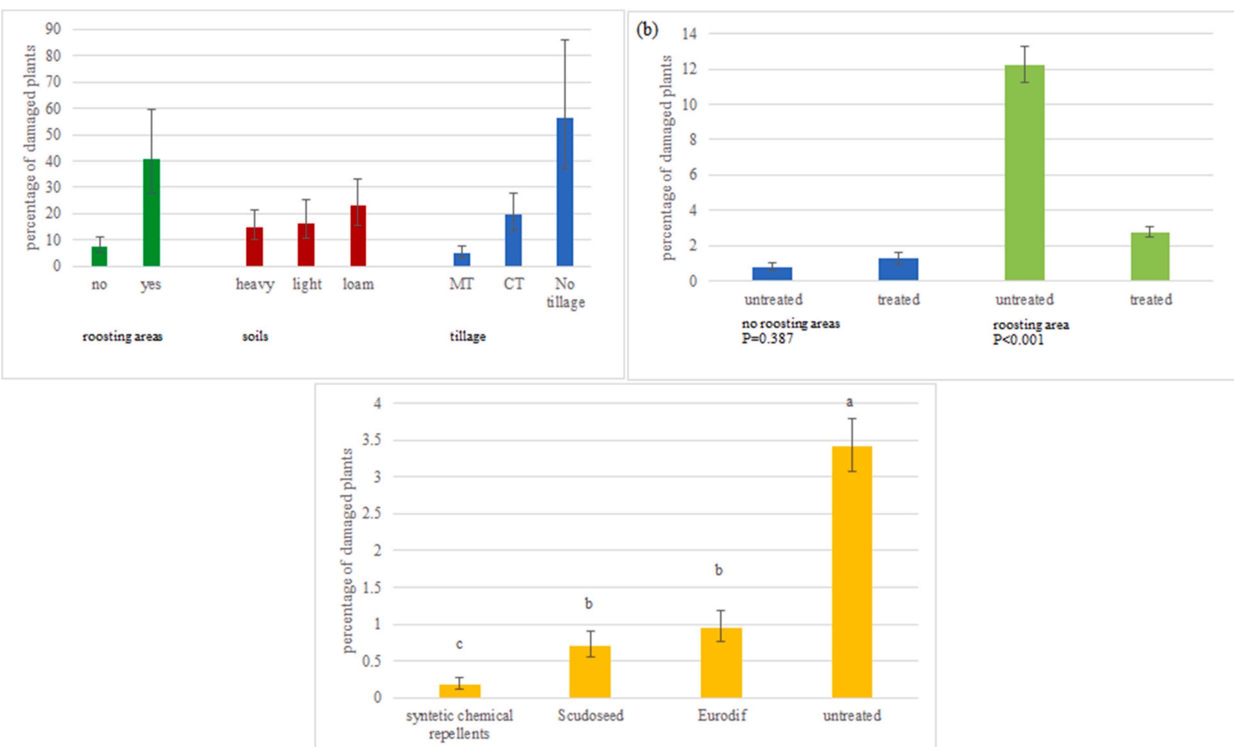

Fig. 2. Results of the generalised linear model analysis. (a) Effect of main risk factors on the percentage of damaged plants by birds (reported predictors were significant at $P < 0.001$). MT: minimum tillage; CT: conventional tillage. (b) Effect of the interaction between treated/untreated and roosting/no roosting areas ($P < 0.001$). (c) Effect of repellent treatments on bird damaged plants. Columns with different letters are significantly different at $P < 0.05$ (post-hoc comparisons with Bonferroni correction). Least squares means and 95% confidence intervals were reported.

conditions; usually no-till fields are sown later, and cause seedlings to emerge slower than in conventional fields, thus these fields are at a susceptible stage, while fields around them are not.

We have found that bird repellents used as seed coatings reduced the risk of bird damage to early growth of maize significantly when compared to untreated fields. Even though repellents with regulated synthetic active ingredients were slightly more efficient in reducing the risk of early damage to maize by birds than naturally derived repellents, the risk of bird damage to maize treated with naturally derived repellents was well below the threshold of 15%. Collectively, these data suggest that the naturally derived bird repellents could be used for effectively protecting maize from bird attacks at early crop stages. In line with these findings, Sandhu et al. (1987) found that seeds coated with fungicide (Thiram) and with insecticide (Methiocarb 0.5%) had a significant repellent effect on birds. Both treatments reduced bird damage to maize at early stages when compared with standard uncoated seeds, but with no significant differences between them. Similarly, there was less maize seed eaten by crows, ravens, black birds, starlings, grackles, Canada geese, gulls, wild turkeys (DeLiberto and Werner 2016; Wise, 2018: Werner et al., 2009), horned larks (Werner et al., 2015) and sandhill cranes (Blackwell et al., 2001; Barzen and Ballingher, 2018), when treated with anthraquinone vs control of non-treated seed in newly planted maize. Esther et al. (2013) conducted a study in Germany to evaluate the efficacy of three different substances (anthraquinone, pulegone and methyl anthranilate) as bird repellents. They found that wild pigeons in aviaries preferred untreated seeds compared to treated ones, with the highest feeding deterrent effect occurring with pulegone 1.4 mL kg-1 and methyl anthranilate 0.085 mL kg-1. However, when the same test was replicated in open fields, where the greatest damage was due to pheasants, none of the substances used had a statistically significant repellent effect; in fact, the birds were observed feeding on coated seeds in the absence of better alternative food sources.

Previous studies have indicated that landscape modifications can modify bird population dynamics (Marzluff et al., 2001; Soldatini et al., 2006; François et al., 2008; Hetmanski et al., 2010; Canavelli et al., 2014). Similarly, based on the risk factors described in this study, prediction of corvid population patterns can be made. In order to reduce the risk of corvid damage at maize establishment, or whenever the population levels of these species are becoming too high, as a prevention measure, landscape modifications and control systems could be applied. For corvids, the best methods are Larsen or Letter-box capture systems (Chesness et al., 1968; Larsen, 1970; Bolton et al., 2007), which consist of cage traps for capturing corvids alive. These methods can be very effective at reducing the impact of corvids on affected crops, even though they are rather onerous to implement in terms of operator time and effort.

5. Conclusions

Risk assessment outputs such as those presented in this study can be used to map cultivated areas with the highest risk of bird damage due to a higher density of roosting areas bordering cultivated fields and to plan prevention strategies (1st IPM principle), such as landscape modifications and bird-population control programmes, and/or to plan sustainable maize early-stage protection, such as the use of naturally derived seed-coating repellents. Following bird population dynamics, particularly population increases, it is possible to keep the damage risk low. Bird damage risk assessment makes it also possible to set up balanced low-cost insurance tools covering farmers' economic risk from maize bird-damage that results in a much lower cost than prophylactic crop protection with no negative environmental impact. Our results of long-term observations in north-eastern Italy indicate that risk from early damage to maize by birds is low and that the use of generalised prophylactic chemical treatments is not justified. A simple insurance approach (see Furlan et al., 2018, 2020 for more details) may be sufficient to guarantee farm income and has no negative effects on human beings or the environment; in areas with factors that increase the risk from early damage to maize by birds, the abovementioned preventive interventions can be combined with the insurance approach.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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