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Bird damage to sunflower: international situation and prospects☆

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Abstract – Bird damage to sunflowers (*Helianthus annuus*) degrades the profitability of this crop and calls into question its place in rotations. Our international literature review shows that sunflower is one of the crops most vulnerable to bird attacks. However, these predatory pests are not specialized: if the sunflower is affected in one region, then the other crops sharing the same cycle could also be affected to varying degrees. All production areas are affected by flowerhead damage at maturity. Damage at emergence has recently become more visible in France, Italy and Switzerland, probably as a result of global changes and evolving farming practices. Birds are highly mobile pests with complex behaviour. The problem needs to be tackled in a hierarchical framework that takes into account field, landscape, and regional scales, along with processes at different timescales from rapid field selection to long term demographic trends. Moreover, the distribution of damage is asymmetrical: few fields are affected, but with a high severity. At this time, there is no single effective method for preventing damage, and coordination at the landscape scale should be initiated to find potential solutions. Finally, there is a gap between theoretical and applied knowledge, even though initiatives in North America have helped to move research forward. These difficulties imply an integrated approach combining partially effective methods, the association of several stakeholders, and the coordination of several policies (agricultural, environmental, and recreational hunting or wildlife management). Additionally, data collection appears essential to acquire knowledge about economic damage and efficacy of control programmes. Digital technology can be useful for such purposes. Finally, this review advocates international networking to consolidate a research community on this topic and on the wider issue of bird damage to crops.

Keywords: sunflower / bird damage / review / research agenda

Résumé – Dégâts d'oiseaux au tournesol situation internationale. Les dégâts d'oiseaux au tournesol (*Heliantus annuus*) dégradent la rentabilité de cette culture et remettent en cause sa place dans les rotations. Notre revue de la littérature internationale montre que le tournesol et une des cultures les plus vulnérables aux dégâts d'oiseaux. Néanmoins, ces bioagresseurs ne sont pas spécialisés : si le tournesol est affecté dans une région, alors les cultures partageant le même cycle cultural pourront aussi l'être à des degrés variés. Toutes les zones de production sont affectées par des dégâts sur capitules à maturité. Les dégâts à la levée ont gagné en visibilité récemment en France en Italie et en Suisse, probablement en lien avec des changements globaux et des évolutions de pratiques agricoles. Les oiseaux sont des organismes très mobiles avec des comportements complexes. La question doit être abordée dans un cadre hiérarchique incluant les échelles spatiales du champ du paysage et de la région, ainsi que des échelles temporelles allant de la sélection des champs à court terme à des processus démographiques à plus long terme. La distribution des dégâts est asymétrique : peu de champs sont touchés, mais avec une grande sévérité. À l'heure actuelle, il n'existe pas de méthode unique et efficace pour prévenir les dégâts, et une coordination à l'échelle du paysage semble indispensable pour aboutir à des solutions. Enfin, il existe un écart important entre les connaissances théoriques et applicables, même si des initiatives en Amérique du Nord ont contribué à faire avancer la recherche. Ces difficultés impliquent une approche intégrée combinant des méthodes partiellement efficaces, l'association de plusieurs acteurs, et la coordination de plusieurs politiques (agricole, environnementale et cynégétique). La collecte de données est essentielle pour acquérir des connaissances sur les impacts économiques et l'efficacité des programmes de prévention. Les technologies numériques

☆ Contribution to the Topical Issue "Sunflower / Tournesol".

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peuvent être utiles à ces fins. Enfin, cette revue préconise le développement de réseaux internationaux afin de consolider une communauté de recherche sur ce sujet, et sur la question plus large des dommages causés par les oiseaux aux cultures.

Mots clés : tournesol / dégâts d'oiseaux / revue / agenda de recherche

1 Introduction

Bird damage to sunflower (*Helianthus annuus*) is an example of a more general problem affecting many crop production chains: cereals, pulses, vegetables, fruit and vines are subject to recurrent and sometimes alarming bird damage (De Grazio, 1978). This problem has been known since the beginning of agriculture. Yet it has historically been little addressed by research. At the international level, there are no learned societies, congresses or specialized journals on the subject, although generic journals sometimes address this issue (*i.e. Crop Protection*, *Journal of Wildlife Management*, and *Human-Wildlife Interactions*). The field of agronomy does not have a specialization pertaining to vertebrate pests like it does for biotic stresses, phytopathology, entomology, or weed science. Bird damage is therefore a rather marginal and little recognized object of agricultural research, in need of evidence-based reports to establish severity of the problem. This is at least the case in Europe because in North and South America, as we shall see in the following sections, the subject has had a different history with government involvement and other traditions of work on human-wildlife relations. It is also a controversial subject on which various stakeholders may have views that are difficult to reconcile. Birds are highly charismatic organisms that are mobile and capable of learning and decision-making. A balance is required between the conservation of native species, the economic well-being of farmers, and the recreational interests of hunters.

This article is a review that attempts to illustrate the problem and propose avenues to reach a solution. First, we will deal with the severity and evolution of damage by describing three documented cases. Secondly, we will detail the theoretical and empirical knowledge needed to understand and predict damage. Third, we will discuss the current control methods and those currently being studied. Finally, we will propose future lines of work. This review is partly taken from the bibliography, which is rather limited, with a large amount of grey literature that is difficult to access, and a lack of universally accepted keywords that reflect the marginality of the subject. We will therefore supplement it with a four-year experience on bird damage studies and prevention programmes at Terres Inovia, the French technical institute for oilseed and seed legume crops, as well as the results of a workshop on the subject conducted with American and European colleagues in March 2019.

2 Qualification and quantification of damage

2.1 Overview

Facing scepticism from stakeholders outside the agricultural sector, the recognition of bird damage as a serious issue is a major challenge. This point is difficult for farmers to accept, but recognition is necessary for a good management of the problem. In practice, this means economic impact studies are necessary for public acceptance. In very practical terms, this means providing figures to public authorities and funders before research or action plans to reduce bird damage can be carried out. The situation becomes paradoxical when quantification requires significant resources because of the great spatial heterogeneity of crop damage and the broad landscape scale in which avian flocks can cause damage. This vicious circle, "Provide evidence to obtain funds"/"Provide funds to obtain evidence" probably explains in part the stagnation of research on the subject. We also need to include the historical perspective and communicate why we should be concerned about this problem today and how modern-day agricultural practices or the changing landscape and climate may be impacting the severity of damage.

Bird attacks on sunflowers are traditionally associated with damage on heads. The review by Linz and Hanzel (1997) on the subject mainly considers this type of damage and shows that all continents are affected. The main species involved belong to the families *Passeridae*, *Corvidae*, *Icteridae*, *Columbidae*, *Cacatuidae* and *Psittacidae* (Tab. 1 and Fig. 1). This review cites damage at emergence for only two species of *Columbidae* in South America. A 1967 work on the French case (Collective, 1967) does not mention this type of damage either, which has been the subject of increasing concern for about fifteen years, to our knowledge in France, Italy (pers. comm. F. Pellegrini), and Switzerland (pers. comm. A. Baux). The species involved in this damage at sunflower emergence are *Columbidae* and *Corvidae*. This is probably a rather new phenomenon, at least in terms of media visibility. Indeed, as the oldest engineers and technicians of Terres Inovia recall, emergence damage has been known to French farmers since the sunflower boom in the 1980s.

To illustrate the level of damage in more detail, we will deal with three contrasting cases for which we have data: the damage of blackbirds (*Icteridae*) on flower heads in the USA, of *Psittacidae* and *Colombidae* in Argentina, and of *Colombidae* and *Corvidae* at emergence in France.

2.2 Presentation of documented cases

2.2.1 *Icteridae* damage at maturity in the northern Great Plains

In North America, blackbirds refer to several species of *Icteridae*, with the red-winged blackbird (*Agelaius phoeniceus*) as the main species, not to be confused with the common blackbird (*Turdus merula*) in Europe. The damage caused by North American blackbirds to crops has been the subject of significant investment since the early 1970s to establish severity and economic impact and propose solutions (Linz *et al.*, 2011). In the United States the federal government has a specialised service to deal with human-wildlife conflicts: the U.S. Department of Agriculture (USDA), Animal and Plant

Table 1. Sunflower depredating species cited by Linz and Hanzel (1997).

Continent	Family	Common name	Latin name
North America	*Icteridae*	Red-winged blackbird	*Agelaius phoeniceus*
	Icteridae	Common grackle	*Quiscalus quiscula*
	Icteridae	Yellow-headed blackbird	*Xanthocephalus xanthocephalus*
	Passeridae	House sparrow	*Passer domesticus*
	Passeridae	American goldfinch	*Carduelis tristis*
South America	*Psittacidae*	Monk parakeet	*Myiopsitta monachus*
	Columbidae	Eared dove	*Zenaida auriculata*
	Columbidae	Spot-winged pigeon	*Columba maculosa**
	Columbidae	Picazuro pigeon	*Columba picazuro**
Europe	*Passeridae*	Eurasian tree sparrow	*Passer montanus*
	Passeridae	Spanish sparrow	*Passer hispaniolensis*
	Columbidae	Eurasian collared dove	*Streptopelia decaocto*
	Columbidae	European turtle dove	*Streptopelia turtur*
	Corvidae	Unspecified	Unspecified
Asia	*Psittacidae*	Rose-ringed parakeet	*Psittacula krameri*
	Psittacidae	Alexandrine parakeet	*Psittacula eupatria*
	Corvidae	House crow	*Corvus splendens*
	Passeridae	House sparrow	*Passer domesticus*
	Passeridae	Spanish sparrow	*Passer hispaniolensis*
	Corvidae	Crows	Unspecified
	Columbidae	Dove	Unspecified
	Columbidae	Speckled pigeon	*Columba guinea*
	Columbidae	Red-eyed dove	*Streptopelia semitorquata*
Australia	*Cacatuidae*	Sulphur-crested cockatoo	*Cacatua galerita*
	Cacatuidae	Galah	*Eolophus roseicapilla*

* Damage reported at maturity but also at sunflower emergence.

Health Inspection Service (APHIS), Wildlife Services (WS), which has a research centre dedicated to researching tools and methods to minimize wildlife damage and human-wildlife conflict (National Wildlife Research Center – NWRC). The Vertebrate Pest Conference enables exchanges mainly between North American researchers specialised in this subject (Marsh, 2008). A recent study gives a numerical evaluation of the damage caused by these birds to sunflowers in terms of yield loss and indirect economic loss to the state of North Dakota (Ernst *et al.*, 2019). In this section, we take up the main points of this study.

Sunflower for oil and confectionery produced in the USA is concentrated at 75% in the Prairie Pothole region of South Dakota, North Dakota, and Nebraska (413 000 ha in 2017). Blackbird damage to the mature head is considered by growers in this region to be one of the main production problems. Producers also cite bird damage as the cause of the recent decline in sunflower acreage, with sunflower being more affected than corn (Klosterman *et al.*, 2013). It should be noted that no source mentions the existence of damage at sunflower emergence. Damage starts fairly early with a maximum 18 days after anthesis (Cummings *et al.*, 1989). The birds are then in the post-nuptial phase, grouped in large flocks.

The damage to the head makes it possible to estimate the loss of yield fairly accurately. A federal survey was carried out with considerable resources between 2009 and 2013 on a total of 721 fields (Ernst *et al.*, 2019). The data made it possible to calculate the direct impact on producers' income and the indirect impact from a macroeconomic model of the production chain that predicts the consequences on employment and consumer purchasing power. Yield losses on fields were estimated on average at 2.59% (sunflower for oil) and 1.66% (confectionery) with strong variations depending on the state. Of the fields reporting losses of more than 5%, 15% were considered as significantly damaged. Total economic losses are estimated at $28.6 million, of which $17.56 million is attributable to direct losses. The objective of the study and the choice of indicators were explicitly designed to convince managers to become more involved in the issue.

2.2.2 *Psittacidae* and *Columbidae* damage at maturity in Argentina

Sunflowers occupy an important place in Argentina (1 819 045 ha in 2017, source FAOSTAT) mainly in a 500 000 km^2 basin along the Rio Uruguay. It is one of the main crops predated by birds (Bruggers *et al.*, 1998). Damage is mainly attributed to *Columbidae* (eared doves) at emergence and *Psittacidae* (especially monk parakeets) at maturity. Monk parakeets are sedentary birds that builds collective nests in trees and feeds on a variety of seeds and fruits, including sunflower, maize (*Zea mays*), and sorghum (*Sorghum bicolor*).

A 1980 FAO study reported by Bruggers *et al.* (1998) estimated total damage to field crops in Argentina at $36 million. In 2012, surveys conducted in Santa Fe province (Vitti and Zuil, 2012) and la Pampa province (Bernardos and Farrel, 2012), showed that respectively 21 and 35% of the fields of sunflower at maturity suffered more than 5% damage,

Fig. 1. Major sunflower predatory birds cited in this article, from top to bottom, and left to right: Male red winged blackbird (*Agelaius phoeniceus*) – By Walter Siegmund (talk) – Own work, CC BY-SA 3.0; https://commons.wikimedia.org/w/index.php?curid=5941742, and female By Cephas – Own work, CC BY-SA 3.0; https://commons.wikimedia.org/w/index.php?curid=7022757. Monk parakeet (*Myiopsitta monachus*) – By Lip Kee Yap – originally posted to Flickr as Monk Parakeet (*Myiopsitta monachus*), CC BY-SA 2.0; https://commons.wikimedia.org/w/index.php?curid=5033536. Rook (*Corvus frugilegus*) – By Rafa-Komorowski – Praca w-asna, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=3203876. Carrion crow (*Corvus corone*) – By Jiel Beaumadier (http://jiel.b.free.fr) – Own work, CC BY-SA 4.0; https://commons.wikimedia.org/w/index.php?curid=34442280. Woodpigeon (*Columba palumbus*) – By Jpbazard Jean-Pierre Bazard – Own work, CC BY-SA 3.0; https://commons.wikimedia.org/w/index.php?curid=20646497.

and respectively 4 and 12% more than 20%. Damage was mainly attributed to *Psittacidae* (monk parakeet) in Santa Fe province and *Columbidae* (eared dove) in La Pampa. The study by Canavelli *et al.* (2014) gives an average rate of 4.29% of plants damaged by monk parakeets, whereas maize was only damaged at 0.9%.

2.2.3 *Columbidae* and *Corvidae* damage at emergence in France

In France, sunflower is a major crop in certain production basins with a national area of 553 000 ha in 2018 (source: Agreste). Although damage from passerines on flower heads has existed since the introduction of sunflower (Collective, 1967), damage from *Columbidae* and *Corvidae* at emergence has been the subject of increasing concern among French producers over the last fifteen years. The declarative survey on oilseeds and pulses conducted by Terres Inovia since 2016 (Sausse and Robert, 2017) shows that sunflower is the main crop affected (80%), that all production basins are concerned, and that damage at maturity only constitutes 3% of the damage declarations. Wood pigeon (*Columba palumbus*) is the main species declared, followed by the carrion crow (*Corvus corone*) and rook (*Corvus frugilegus*). Other species such as the rock dove (*Columba livia*) or grey and red partridges (*Perdix perdix* or *Alectoris rufa*) are occasionally mentioned. It should be noted that the carrion crows and rooks are also known to attack maize at emergence (Robin, 2011).

According to our field diagnostics, feral and wood pigeons consume the young plants as soon as they emerge at the emergence and cotyledon stages, which corresponds to the Argentinean experience (Collective, 2011). Two trials carried out by Terres Inovia on contrasting situations have shown that the plant is harmed only if the stem is cut (unpublished results). The plant will recover after the emergence of the first pair of leaves, with no impact on yield. As a result, the susceptibility phase is very short: from a few days under homogeneous emergence conditions to two weeks at most on a field. *Corvidae* can attack the sown seeds, or even pull the stems after emergence, as in the case of maize.

Unlike head damage, this early damage makes it difficult to attribute to a pest species without a good knowledge of the symptoms to avoid confusion (slugs, moles (*Agriotes* spp.) or early fungal diseases). If the plant population is the main component of yield, the latter also depends on post-emergence conditions and accidents. The potential will be affected below 50 000 plant/ha (Terres Inovia expertise), with variations depending on the water stress on the field and the spatial heterogeneity of the damage. Losses may be such that producers decide to re-sow. Taking these elements into account, we can distinguish two scenarios with several components of economic losses, for a total of 129 to 228 €/ha (Tab. 2), *i.e.* 14 to 35% of the indicative gross margin.

To this direct impact, we should add the indirect impact of excluding or abandoning sunflowers for fear of damage (Klosterman *et al.*, 2013 in USA, Abid, 2019 in France).

Table 2. Structure and order of magnitude of direct costs attributable to bird damage at emergence under two scenarios with or without resowing. Yield losses for both scenarios are estimated at 12% (Sausse, 2016).

Cost source	Scenario	
	Resowing	Without resowing
Prevention	Equipment (scaring), time spent... Not rated	
Lower yield	Non-optimal planting date: €110	Non-optimal population (density and structure): €129
Price reduction on oil content	Not relevant	
Cost of re-sowing	Passage – seed: €119	Not relevant
TOTAL (excluding prevention)	€229	€129

Removing sunflowers from production can lead to a deterioration in the performance of cropping systems: sunflowers indeed have advantages as melliferous crops and require little pesticides and herbicides. Sunflowers can be a favourable predecessor for weed management in rotations with winter crops such as wheat. Bird damage is a driver for crop selection and thus may limit crop diversification, as indicated by a survey of farmers (Abid, 2019). Finally, the costs (*i.e.*, bird damage management and resowing) may be passed on to the entire value chain (*i.e.* seed production, grain collection, food and feed production), but no such estimate has been made in France.

Damage assessment at the national level is still imprecise. By cross-checking data from the "Vigicultures" pest monitoring network and from surveys on agricultural practices conducted by Terres Inovia, Sausse and Robert (2017) estimate that one third of sunflower fields were visibly damaged. The percentage of sunflower fields suffering high damage with resowing was 13.5% in 2013 and 7.0% in 2017 according to Terres Inovia (survey on agricultural practices) and 7.5% in 2015 according to a survey from the Union Française des Semenciers.

Assuming 10% of the fields are affected and 50% of which are resown, the direct impact on an acreage of 550 000 ha according to the total costs given by Table 2 would range about €10 million at national level each year for the damage at emergence alone, indicating the magnitude of the problem. At present, no system of sampled surveys (*i.e.* the *a priori* choice of fields independent of the risk of damage) makes it possible to accurately estimate the damage incidence and severity at national level and interannual variation.

2.3 Specificities of bird damage

The cases reported above have several things in common. The first is the lack of strict specialisation of birds on sunflower: bird damage affects other crops which follow the same cycle: Sunflower is particularly included in rotations with maize in the USA, soybean (*Glycine max*) and sorghum in Argentina, and maize and pulses in France. On the other hand, the spatial heterogeneity of the damage is underlined both by the American surveys carried out at maturity (Bernardos and Farrel, 2012; Vitti and Zuil, 2012; Klosterman *et al.*, 2013; Linz and Hanzel, 2015) and by those carried out in France at emergence (Sausse *et al.*, in press). The damage shows the same type of distribution: few fields are impacted, but with a severity that strongly impacts a few growers. Heterogeneity is also observed between production basins. This has two consequences: considered globally, the problem can be seen as being of moderate concern (Vitti and Zuil, 2012) or not justifying costly management measures (Klosterman *et al.*, 2013). But at the same time this heterogeneity results in individual crop failures and a strong feeling of insecurity among producers. This pattern results from the high dispersal capacity of birds, their gregarious behaviour and the lack of control tools; a different scenario than that encountered in other pests where damage is more moderate but concerns more fields. The heterogeneity of damage is also found within fields, with apparent gradients from the field edge or randomly distributed holes, further complicating damage surveys and the evaluation of control methods.

Today's focus on environmental issues and agro-ecology encourages us to put the problem in a broader context. Avery (2002), Wenny *et al.* (2011) and Dolbeer and Linz (2016) point out that the cost of depredation must be weighed against the benefits that the species in question bring to society as a whole, including the agricultural sector. Indeed, birds have the ability to provide both ecosystem services and disservices, especially granivores that consume invertebrates during the breeding season. For example, blackbirds are known to be beneficial for the protection of maize against lepidopteran larvae (*Helicoverpa zea* and *Diabotrica spp*.) (Okurut-Akol *et al.*, 1990; Dolbeer and Linz, 2016). The case of carrion crows is a special case because they are nest predators of wood pigeons but are also known to damage crops. The history of China gives a much more dramatic example. The "Four pests" campaign from 1958 onwards resulted in a massive fight against the European tree sparrow (*Passer montanus*). Wenny *et al.* (2011) have suggested that the famine during the Great Leap Forward had to do with the relaxation of the biological regulation of insect pests following this extermination campaign.

3 Biological processes that cause damage

3.1 Need for a hierarchical approach

Understanding why and how birds consume sunflowers is an essential step in devising and testing cost-effective damage prevention methods. Bird damage to crops is the result of processes operating at increasing and nested spatial and temporal scales, following a classical "hierarchical principle" in ecology (Allen and Starr, 1982). Clergeau (1995) applied this principle to European starling (*Sturnus vulgaris*) damage. Here we propose a simplified version of his conceptual model,

Fig. 2. Multi-scale approach to understanding and preventing bird damage.

with three scales (regional, landscape, and field) at which birds make choices (Fig. 2):

- The region where they decide to settle for the season (nesting for emergence damage, post-nuptial phase for head damage), which will determine a pool of birds likely to cause damage;
- The landscape where they select places to eat in their daily activities;
- The field where they look for food items.

3.2 Sunflower as a food resource

The fundamental motivation of birds attacking sunflowers is energetic: they seek to feed themselves or their offspring by consuming seedlings and seeds. The diet of the species involved is known in broad outline. *Columbidae* are almost exclusively herbivorous (seeds and vegetation) while *Corvidae* are omnivorous and opportunistic. The diet of *Icteridae*, like that of many passerines, is mainly insectivorous during nesting and then granivorous. Monk parakeets are mainly granivorous. More precise studies (crop analysis) show that the diet composition depends on the season and the resources available in the environment and on cropping systems at the time of the study. In the case of wood pigeon, Murton (1965) gives rich information but relating to the English agricultural landscapes of the 1960s. More recent work carried out on the autumn-winter period in France (Aubineau *et al.* (2001) in West; Négrier (2018) in South West) indicates an important contribution of maize and sunflower grains. But we found no reference on the diet of wood pigeons in sunflower production basins in the weeks following sowing. The relative interest of sunflower seedlings compared to other resources (seedlings and buds for *Columbidae*, mainly invertebrates for *Corvidae*) is not known. Sunflower seeds are a popular resource for granivorous birds, so much so that varieties have been selected for use in bird breeding and are popular for recreational bird feeding.

3.3 On the field: locating and accessing seeds and seedlings

At first glance, a sunflower field may seem homogeneous. But taking advantage of the resources it offers is not always easy. The birds have solved the problem of locating plants on the field and accessing these resources.

Access to the sunflower depends on the morphology of the birds. A long, sturdy beak will be an asset when searching the ground for seeds: the carrion crow is capable of this, not the wood pigeon. However, no data are available on the potential depth of the search into the ground that occurs for each species. At maturity, accessing the head that slopes towards the ground requires acrobatic skills.

For a bird on its feet, it does not seem to be much more difficult to locate the plants when emerging than for a human looking over the field. Evolution has provided birds with generally excellent eyesight that differs from that of humans in several ways (ultraviolet vision and polarization perception, lower binocular field of view) with variations among species (Bennett and Cuthill, 1994; Osorio and Vorobyev, 2008). The problem is more difficult before emergence. The ability of *Corvidae* to locate buried seeds or plants is surprising. The sensory hypothesis is the most obvious: signals can be detected at a distance. Since noise is implausible, the sense of smell can be evoked. Birds are not devoid of it (Clark *et al.*, 2015). The cognitive hypothesis is also possible, as the birds proceed like any agronomist who is asked to check the status of sown seeds: they interpret the surface state of the fields to locate freshly sown seeds, start by probing at random and then quickly refine their prospecting thanks to their knowledge of the spatial structure of the seeding. Seeding lines can make their task easier by giving a visual clue, but this is not always the case. At first glance, this scenario may seem far-fetched, but the cognitive performance of *Corvidae*, like rational calculation, lying... (Emery and Clayton, 2004; Dufour *et al.*, 2012) makes it plausible. These performances depend on individual (memorisation, reasoning ability) and social (ability to exchange and interpret information) skills. Pigeon has the reputation of being less intelligent, which does not encourage studies to be conducted to verify this.

Once the resource has been identified, the last problem for the birds is its *a priori* evaluation: is it good to eat? The senses play an important role here. Work by a group of student agronomists for Terres Inovia has shown that the colour of seeds has an effect on their selection by *Corvidae* (Aublet *et al.*, 2018). It has been shown that birds have taste preferences (Clark *et al.*, 2015), for example an aversion to bitterness. Smell may also play a role. Several reviews (Douville de Franssu, 1997; Avery, 2003) specify how these physiological processes can be used to develop repellents. The innate repulsion to certain sensory signals is at the origin of so-called "primary" repellents. Primary repellents quickly lose their effect if they do not cause an undesirable physiological effect. This is because birds do not stop at their first impression and may test things that are unpleasant at first glance if they have no choice. This ability likely varies from individual to individual and needs to be addressed at the population level: neophobic individuals will learn from neophiles. Learning and memorization also helps to avoid toxic foods. This principle is used for so-called "secondary" repellents with a neutral taste but causing physiological disorders that birds remember.

It should be noted that some fungicides and insecticides known to have repellent action have been used on sunflowers and other crops in the past. Thus, one of the causes of increased emergence damage could be the withdrawal of products having a toxic and/or repellent effect. In the French context, we can quote in particular (source: E-phy, retrieved on 20 April 2020, from https://ephy.anses.fr/)

- Thiram for use on sunflowers until 2006 as a fungicide seed treatment;
- Carbofuran for use as a generic soil treatment against insects until 2008;
- Methiocarb for use in generic slug control until 2015.

In conclusion, references on the senses and choice behaviour of birds do exist. Do they have the potential to show us the way forward in making operational proposals? This would require precise information on a species-by-species basis, work that goes beyond this generalist review. However, a generic lesson can be learned: the behavioural model is not purely reactive. In other words, the senses are at the service of learning.

3.4 In the landscape: selecting sunflower fields

The visits on fields is the result of a complex process that integrates individual capacities and social behaviour. The latter is important during sunflower emergence, which occurs during nesting and is often associated with territorial behaviour. Nesting wood pigeons can feed outside their territory and usually operate in groups on sunflower fields at emergence. Carrion crows have a territory of several tens of hectares that they will defend fiercely against intruders of the same species (Géroudet, 2010). Damage at emergence is caused by bands of juvenile carrion crows on fields outside the territories defended by adult pairs. Rooks nest in colonies and damage can be caused by bands composed of both adults and juveniles. The coexistence of *Corvidae* and *Columbidae* on damaged fields was occasionally observed during our field trips. The above considerations are rather theoretical because, in the absence of systematic field observations, there is a lack of data to characterize more precisely the identity and behaviour of the birds. At sunflower maturity, *i.e.* outside the breeding season, the birds may aggregate in large, sometimes multi-species flocks and end up in roosts in the evening.

Birds are known to be active at sunrise and sunset. This has been confirmed for feral and wood pigeons by analysis of time lapse images in 2018 at Grignon over the period April–May (Fig. 3). *Corvidae* observed on this field increased foraging behaviour in the afternoon.

Birds locating and choosing sunflower patches depends first and foremost on the birds' ability to move: the home range is an important parameter in determining what is meant here by "landscape". Damage during sunflower emergence (mid-April–May in France) occurs during the nesting period. The movements of nesting birds are then constrained by the location of their nests. Recent work has shown that wood pigeons equipped in Paris with GPS devices move every day on the Saclay plateau about 20 km away (Marchand, 2019). It is unlikely that nesting pigeons in rural areas travel such great distances, but data are lacking. For rooks, the proximity of "crow nests" is a good indicator for predicting attacks (0.5 to 1 km according to Kasprzykowski (2003)). Monk parakeets do not move more than 3 km away from their collective nest throughout the year (Bruggers *et al.*, 1998).

Once these constraints on daily travel have been set, the choice of fields depends on an energy calculation that takes into account the value of the food, the cost of searching and handling food items in the field, and the cost of vigilance behaviour. This calculation is relative: it is not the intrinsic value of the field that matters, but its value compared to that of other surrounding resources. On the other hand, fear of predators may explain the spatial distribution of individuals according to the characteristics of the surrounding landscape. This is what ecologists call the "landscape of fear" (Laundre *et al.*, 2010). This phenomenon is probably important in the case of *Columba* species and needs to be clarified: is it better to be able to retreat under cover or to have a clear view?

Sight will be the preferred sense for searching for food, but smells can play a role in the orientation of pigeons in flight (Benvenuti and Wallraff, 1985). Cognitive and social aspects are essential. Birds do not just fly randomly to the first field that meets the criteria. They take advantage of their experience and potentially scouts who will prospect and share their discovery with the flock, as did the billions of passenger pigeons travelling across the American continent before dying out at the end of the 20th century once the size of their flocks had fallen below a critical threshold (Bucher, 1992). Prospecting can be direct or take advantage of observing the behaviour of other species.

Field selection operates on a scale that makes experimentation difficult. The preferred method of investigation is the interpretation of the spatial distribution of the birds according to the characteristics of the landscape. This correlative approach requires caution because the spatial distribution of birds is the result of different processes. Generalization of results can be tricky (Whittingham *et al.*, 2007; Schaub *et al.*, 2011): A unique class of vegetation formation on a map may in fact correspond to different vegetal formations and subsequent

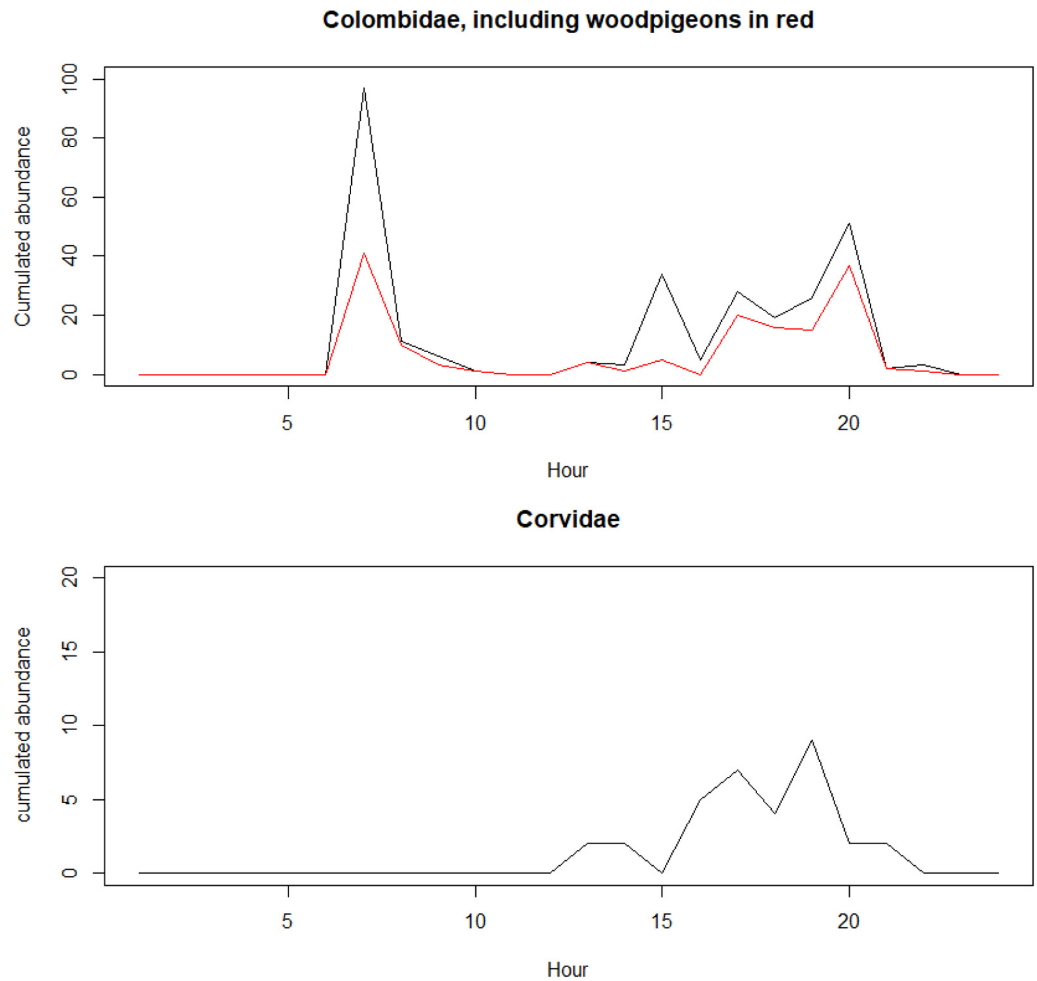

Fig. 3. Cumulative hourly attendance of a sunflower plot in Grignon (Yvelines, France) between 28 April and 23 May 2018. Data obtained from a time-lapse camera set for one photo every 15 minutes.

resources, and the same bird species may have populations with different habits. Nevertheless, the method can allow for local predictions. For example, attacks by blackbirds are more frequent near marshes, which are nesting and roosting areas (Otis and Kilburn, 1988). The French landscape context is generally more complex than the Dakota Plains and studies are currently being conducted by Terres Inovia to determine the impact of the proximity of urban areas, tree features and the density of sunflower fields in the landscape, which we can hypothesize contributes to "diluting" the damage over the whole territory. For the monk parakeet, the presence of trees and other feeding sites in the vicinity determines the damage more than the characteristics of the field (Canavelli *et al.*, 2014). Rooks in Poland, on the other hand, have a predilection for meadows and spring crops and their establishment in such environments has a favourable effect on reproductive success (Kasprzykowski, 2003). This preference for grasslands by rooks has also been observed in England (Mason and Mac Donald, 2004). Although sunflowers are not part of these landscapes, these studies provide clues about the major landscape structures favourable to pest bird species.

3.5 Regional level: settle and prosper... or decline

Wood pigeons are undeniably expanding in France with increasing sedentary populations, and more generally in Western Europe (source: www.vigienature.fr, retrevied on 11 January 2019). In England, this expansion has been attributed to the increase in rapeseed area, which provides a significant food resource in winter and thus improves survival (Inglis *et al.*, 1990). In France, sedentary populations are growing. The reproductive success of the species is higher in urban areas (pers. comm. H. Lormée based on data from the *Columbidae* observatory of the French Biodiversity Office). The wood pigeon's success is symptomatic of that of large specialist species to the detriment of small specialist species, a probable consequence of global change, climate simplification and landscape disturbance, as proposed by Teyssèdre (2016). Carrion crows and rooks, on the other hand, see a certain stability in their numbers, although with changes in their ranges. Is the exploitation of sunflowers, and corn, a response to the increasing scarcity of grasslands, which are rich in invertebrates and for which rooks show a clear preference

(Kasprzykowski, 2003; Mason and Mac Donald, 2004)? Whatever the species, it is likely that the ban on pesticide seed and soil treatments (carbamates and neonicotinoids) may have facilitated seed consumption by birds and the damages in sunflower and maize fields.

In North America, blackbirds remain abundant with a decreasing trend over the last few decades. For example, while the red-winged blackbird is the most abundant species with 300 million individuals, its population decreased by 30% between 1966 and 2014 (North American breeding Bird Survey). This trend is attributed to the decrease in favourable habitats, particularly wetlands and some perennial forage crops such as alfalfa (Blackwell and Dolbeer, 2001). In South America, the monk parakeet owes its success to the development of eucalyptus plantations and the progress of electrification, which provides new nesting sites (Bruggers *et al.*, 1998; Linz *et al.*, 2015).

These different cases suggest that there is no unequivocal link between demographic trends and damage. We can propose two hypothetical scenarios to explain the mechanisms. For wood pigeons, sunflower offers a complementary resource in an environment that has become globally more favourable. The sunflower is a victim of population growth. For *Corvidae* and *Icteridae*, sunflower is a fallback solution in a less favourable environment. It makes it possible to limit the demographic decline. Studies remain to be carried out to prove it.

The cases cited so far concern native species. We can also recall the risks associated with biological invasions. Evoking the damage caused by parakeets on sunflowers in Europe may provoke disbelief today, but it could become a real problem in the years to come according to an assessment about the collared parakeet (Clergeau, 2014). This species, as well as the monk parakeet whose impact in South America we mentioned above, is acclimatizing around several European towns, with already recognized impacts on some infrastructures and feared impacts on agriculture, not to mention those on native species. Vigilance is essential, as action must be taken as soon as possible.

3.6 Summary: pitfalls and avenues

This rapid review shows several processes acting on various scales, making it possible to understand damage and its variations: sensory response, cognition and memory, intra- and interspecific interactions, demographic dynamics and, in the very long term, morphological adaptation. These processes should not be considered in isolation, as paradigms offering self-sufficient heuristic frameworks. They act in concert. Forgetting this can be dangerous. For example, agronomists tend to consider only sensory reactions with reference to the well-known case of insects that react in a fairly predictable way to chemical signals. The notion of food “palatability” can be a trap, since preferences observed at the time incorporate various processes, of which the intrinsic characteristics of the food are only one component. Returning to time $t+1$ or presenting foods in another context may yield different results. Conversely, considering only the impact of global changes (climate, landscape) on the demography of species is obviously very useful for anticipating problems and guiding general policies, but gives little hope to producers.

The multi-scale approach is therefore necessary and implies multi-stakeholder collaboration and being able to link the results into a coherent and usable whole. However, scaling up poses a problem of generalization. While experiments under controlled conditions (*e.g.* in aviaries) can be conclusive, the move to the field and then to the territory brings in new factors of variation that blur the answers. A difficult point is the question of adapting the behaviour and choice of birds as one moves closer to natural conditions. We will come back to this in the section devoted to field control methods and, in particular, the development of repellent products.

Another difficulty is the evolution of the processes at work, especially in the context of global changes (climate, landscape, biological invasions...) and therefore the possible lack of available and updated references. The behaviour of birds is variable over time. A species specialised in a habitat type, such as the wood pigeon once considered as a forest pigeon, can become a generalist in a few decades depending on historical opportunities: new resources emerge that must be learned to exploit, others decline, competitors become more aggressive, others disappear. Moreover, variations between populations are quite possible for a given species. Even the family structure can vary geographically: young Spanish carrion crows live with their parents, while French crows become independent more quickly (Baglione *et al.*, 2002). This may have consequences for the exploitation of the environment including crops.

Ultimately, while ecology provides a general framework and concepts for thinking about the problem of damage, relatively little applicable knowledge is immediately available to identify prevention solutions. Generalisation is a recurrent issue in ecology and this debate is important in our case, because we want to use knowledge to identify prevention strategies.

Faced with these difficulties in generalizing in time and space, it is important to “localize” the knowledge (choice of species in the study areas and seasons) and to update it. This poses an economic problem if one considers the extent of the studies to be carried out. A first way is to take advantage of unpublished expertise, particularly among hunters and naturalists. It is abundant but scattered. On the other hand, digital technologies can greatly reduce data acquisition costs. We will give a few examples of technology and their application:

- Optical sensors coupled with automatic image analysis: frequency of birds in the fields (*e.g.* work in progress within the framework of the Carnot Institute’s Plant2Pro® project “C3-PO: Counting, mapping and characterizing for better prevention of bird damage”);
- GPS beacons: bird movements and other physiological information (*e.g.* Marchand (2019) for application in the case of wood pigeons);
- Participatory science tools: collection of field data and feedback on prevention methods (*e.g.* declarative survey by Terres Inovia (Sausse, 2016));
- Geographic information in open data on landscapes and crops: spatial analysis of damage patterns;
- Satellite data for damage mapping at maturity (Klug, 2017). The concept of classifying fields according to plant number, which provides an indication of emergence damage, is undoubtedly possible but remains to be proven.

Table 3. Reviews on control methods. This list is non-exhaustive. Grey literature exists without being easily accessible, especially in the area of airport protection.

Reference	Sectors	Species	Methods	Main focus
Collective, 2011	Crops	*Columbidae*	All	Review
Avery, 2003	Crops	All	Repellents	Review and Forward-Looking
Baumgartner *et al.*, 2019	Crops	All	All	Review (management of the positive and negative aspects of avian biodiversity)
Bishop *et al.*, 2003	Crops	All	Scarecrows and all alternatives	Review and Forward-Looking
Bomford and O'Brien, 1990		All	Sound scarecrows	Review
Bruggers *et al.*, 1998	Crops	*Columbidae, Psittacidae*	All	Thinking about planning actions in Argentina and Uruguay
Clark, 1995	Crops	All	Chemical repellents	Review
Clark, 1998	Crops	All	Chemical repellents	Review
DeLiberto and Werner, 2016	Crops, Forestry	All	Anthraquinone	Review for all uses
Dolbeer and Linz, 2016	Crops	"Blackbirds"	All	Review
Douville de Franssu, 1997	Crops	All	Repellents	Review
Erickson *et al.*, 1990	Any use case	All	Falconry	Review
Gilsdorf *et al.*, 2002	Any use case	Birds and mammals	Scarecrows	Review
Linz and Hanzel, 2015	Sunflower	All	All	Review
Linz *et al.*, 2012	Sunflower	"Blackbirds"	Nonlethal	Review
Linz *et al.*, 2011	Sunflower	"Blackbirds"	All	Review
Linz *et al.*, 2015	Crops	All	Lethal	Review and Forward-Looking
Harris and Davis, 1998	Airport	All	All	Review
Linz *et al.*, 2017	Sunflower Corn, Rice	"Blackbirds"	All	Review and Forward-Looking (Reference Book)
Parrot *et al.*, 2014	Oilseed rape	"Woodpigeon"	All	Review
Tayleur and Henderson, 2007	Oilseed rape	"Woodpigeon"	All	Review
Wang *et al.*, 2017	Crops	All	Biomimetic Drones	Survey on existing methods

4 Review of control methods

4.1 Sources: many reviews and few studies

The literature proposes several reviews of bird control methods aimed at managers in various sectors, including agriculture but also airports because of the issue of collisions (Tab. 3). In particular, Linz *et al.* (2017) synthesizes blackbird management research, in its applied and prospective aspects. These reviews, ours being no exception, list practices applicable on a limited or extended scale, the effectiveness of which is relatively unsupported by original studies. Thematic reviews are proposed on specific methods such as scaring devices, repellents and population regulation.

4.2 Eliminating troublemakers: a traditional but controversial method

4.2.1 Destruction by individual farmers

Lethal removal strategies are opportunities for farmers to protect their crops. These possibilities must meet two conditions: the use of legal means of destruction and respect for the legal status of the species. The latter varies from country to country and implies a more or less strict framework. We will present the French and American cases by way of example.

In the French context, shooting or trapping for destruction by individuals is authorized under several conditions (Sausse *et al.*, 2017):

– The species must be declared "likely to cause damage". Wood pigeons, carrion crows and rooks may be declared "likely to cause damage" at the departmental level on the decision of the prefect after consultation with the departmental hunting and wildlife commissions involving various stakeholders. The common pigeon (*Columba livia*) does not fall within this framework because its status is not that of a true wild species;
– An authorization must be requested at the local public authority;
– The species must be destroyed by an authorized person (with a license) using methods (shooting or trapping) prescribed by the law.

In the USA, blackbirds have been protected under federal law since 1918 (Linz *et al.*, 2017). However, they can be destroyed without federal permit in case of damage or health risk (source: code of federal regulations, title 50, section 21.43). Two species whose status is of concern, the rusty blackbird (*Euphagus carolinus*), and tricolored blackbird (*Agelaius tricolor*) are excluded from this system.

4.2.2 Population control

The regulation of populations is a more ambitious objective that requires the intervention of public authorities to act directly or at least coordinate actions.

In France, administrative hunt campaigns are used to respond to crisis situations at the departmental level, including against protected species. The "adaptive management" of fauna according to population objectives requires long-term planning. It is implemented by hunters on certain populations of hunted birds and mammals, but not on the species mentioned in this article, although this may change in the near future. The case of the wood pigeon puts the impact of regulation into perspective. This species, which is very popular with hunters, is the subject of large numbers of takings, 5 million individuals in 2013–2014 in France according to Lormée and Aubry (2018), but which do not allow populations to stabilize.

The review by Linz *et al.* (2015) examines several cases of regulation in North and South America. In the USA, government-sponsored regulation trials of blackbirds have been conducted using trapping and poisoning methods adapted to avoid non-target species. The authors conclude that they are ineffective. In Argentina, the eared dove underwent a massive campaign in the 1960s that included poisoning, subsidies for hunting, and promotion of its consumption. This campaign proved to have no effect on the populations. The monk parakeet presents in principle features favourable to a control of the populations (long lived species not very prolific and gregarious). It has also been the subject of local programmes, with the use of poisoning methods, the effectiveness of which on damage has not been evaluated. Populations recovered a few years later. The paper gives other examples and discusses the failure of these operations, highlighting several points:

- Prolific species with a high dispersal capacity such as *Columbidae* appear to be very resilient. The immigration of birds from uncovered areas can cancel out the effect of the removals. The latter play little role in relation to the global factors that determine populations. Given the logistical difficulties of these operations, the benefit/cost ratio is low; Murton *et al.* (1964) reach the same conclusions on the basis of monitoring a regulated population of wood pigeons in England;
- Controls (poisoning) pose risks to non-target species and tend to be reduced due to environmental policies;
- The public may be reluctant to do this;
- There is a lack of steering to define objectives and monitor the effectiveness of operations.

The authors do not reject population control but insist on the initial diagnosis and steering of operations, as well as on the combination of different levers. They point out that regulation can use non-lethal methods such as reproductive inhibitors (*e.g.* Avery *et al.*, 2008a, 2008b).

The conclusions can be applied to the French context, where the debate around the destruction of pest birds can be lively. To date, there is no monitoring system linking the level of populations, removal and destruction for crop protection purposes, and damage to crops. We can add the specificity of the closer interweaving of urban and agricultural areas. Birds nesting in cities can feed in the surrounding countryside. This has been shown on the Saclay plateau near Paris (Marchand, 2019). Consequently, involving the urban sector could be a strategy that pays off, although to our knowledge no consultation with the municipal services in charge of these issues has been implemented in France.

4.3 Field-based methods: still largely empirical

4.3.1 Repellents

The reviews of Douville de Franssu (1997) and Avery (2003) give a good overview of the subject. Repellents can be used as seed coatings or aerial treatments. The primary ones have only an irritant action, the secondary ones a non-lethal toxic action causing conditioned aversion. Secondary repellents are known to be more effective than primary repellents (Douville de Franssu, 1997). This effectiveness can be enhanced by flavours or colours that make it easier for the bird to identify the food (Avery, 2003; Mason and Reidinger, 1983). The best-known secondary repellents are methiocarb, also used as slug repellents, dithiocarbamates, also known for their fungicidal action, and anthraquinone. Methiocarb and dithiocarbamates likely have a lethal effect that causes repellency at lower concentrations.

Primary repellents are varied in nature. Some have been the subject of in-depth studies (methyl-anthranilate in the USA, cinnamamide in Great Britain). Clark and Shah (1994) have proposed generic chemical structure criteria for the efficacy of these products using the European starling as a model species. Some preparations are obtained by an empirical trial/error process. This is the case for preparations based on essential oils and chilli peppers with repellent claims, which are now marketed in France for full or seed coating treatments. Trials conducted by Terres Inovia on a network of fields did not show sufficient effects to justify advice (Sausse and Robert, 2017). Such product marketed as "Flock Buster" in the USA was found ineffective in a laboratory testing on blackbirds eating rice and sunflower seeds (Werner *et al.*, 2010).

The NWRC conducted screenings of several hundred products in the 1970s (Schafer *et al.*, 1983), some of which resulted in cage and then field tests. Linz *et al.* (2011) have reviewed this work and only retain anthraquinone as potentially effective on sunflower. Anthraquinone has been shown to be effective as seed treatments on emerging sunflower seedlings to protect from ring neck pheasant (*Phasianus colchicus*) (Werner *et al.*, 2011) and as aerial treatment on emerging soybean to protect from Canada geese (*Branta canadensis*) (Werner *et al.*, 2019). Werner *et al.* (2011) showed the potential of anthraquinone to protect the flower heads from blackbirds but a lack of effective application strategies to the face of the downward facing head deems it ineffective for sunflower (Kaiser, 2019).

The specialized and generic reviews in the Table 3 indicate that research on these products and their use faces three obstacles. First, these products are difficult to register for "bird" use, either because of their toxicity or because of registration costs related to the small size of the market (*e.g.* Eisemann *et al.*, 2011 in the case of fruit crops). The situation for some products is unclear. Some have a "not for original purpose" use (*e.g.* methiocarb, still used as a slug control agent in some countries). Others are marketed as bio-stimulants or fertilizers with repellent claims. The "natural" origin of some products (*e.g.* anthraquinone can be extracted from certain plants) is evoked to justify their possible use on organic crops. As it stands, no repellent product is registered for use on sunflowers in France. Methyl-anthranilate and anthraquinone are registered in some New World countries. On the other hand, the application of the products is delicate, especially in the case of foliar treatments. Emergence treatments are carried out on almost bare soil with little persistence of action. A systemic mode of action could overcome this obstacle (Esther *et al.*, 2013), as well as the use of adjuvants. For example, Cotterill *et al.* (2004) found a better repellent effect of cinnamamide applied to rapeseed leaf with an adhesive formulation. Capsular treatments are difficult to perform without specialised equipment (*e.g.*, high clearance tractor or aircraft). Linz *et al.* (2011) propose the development of nozzles adapted to spray the down leaning side of flower heads and thus reach the achenes. Finally, the effectiveness is partial, depending on the pest species, and is difficult to confirm when moving from aviary to field, as pointed out by Bishop *et al.* (2003) and Kaiser (2019). Linz *et al.* (2011) deplore this, establishing the poor operational results of the work carried out since the 1960s by the NWRC to protect flower heads from blackbird. Concerning the protection of sown seeds and seedlings (Esther *et al.*, 2013) tested on pigeons, the effect of three repellents (anthraquinone, methyl anthranilate, and pulegone) coating maize seeds. The pigeons showed an aversion to the seeds coated with methyl anthranilate and pulegone, but not to the emerged seedlings. But no effects were observed in the field: as control over environmental factors decreases, birds face new problems and see their opportunities for choice changed.

4.3.2 Bird scaring devices

Numerous models of sound and acoustic bird scarers are available on the market. Several types of signals are used alone or in combination (Avery and Werner, 2017):

- Sounds

  - Detonation: propane cannons, pyrotechnics, or shotguns;
  - Signals recorded: distress cries, predator calls, or other loud noises.

- Visuals

  - Human figure, predator (balloon, human figure, kite);
  - Dead bird effigies;
  - Handheld or fixed or automated laser;
  - Pendulum or reflective tape using the sensitivity of birds to the polarization of light.

All reviews discussing these methods point out that their effectiveness is limited by a reduced range and habituation of the birds. The review by Gilsdorf *et al.* (2002) concludes that effectiveness is partial and best when control methods are combined, except for ultrasound, which is ineffective. Harris and Davis (1998) propose to condition the birds by coupling frightening signals and actual danger. All agree that the use of scaring devices must be sporadically and rarely used for best effectiveness. This advice also applies to the human species: the use of sound models is regulated in France by regulatory provisions to avoid problems with neighbours.

Studies producing data on the effectiveness of bird scarers are rare or are limited to qualitative assessments. Bomford and O'Brien (1990) pointed out the formidable methodological and statistical challenges of experimentation in this field, where the variability and scope of the processes is unusual for the experimenter. Cummings *et al.* (1986) have shown the effectiveness of propane guns on blackbirds, but on small areas (2–3 ha). Personal observations showed a rapid habituation of the pigeons in case of frequent use of the gas cannons (20 min interval) with a return to the vicinity of the device within minutes after the explosion. Bomford (1990) concluded that a tape acoustic device is ineffective on European starlings (*Sturnus vulgaris*), as well as Conover and Dolbeer (1989) for reflective strips on blackbirds. Santilli *et al.* (2012) tested a helium balloon on maize and sunflower fields with good results. Blackwell *et al.* (2002) observed a limited effect of lasers on common pigeons (*Columba livia*), but better on American crows (*Corvus brachyrhynchos*). Hunter (1974) found a deterrent effect of dead or dummy wood pigeons to protect cabbage or rapeseed crops.

Three avenues for improvement are now being considered:

- improving and adapting signals to target species based on knowledge of ethology;
- extend the range of the disturbing signal using air or ground-based UAVs. Technologies are now mature to program the flight of autonomous UAVs. French regulations do not allow this use: an operator must remain within range. The shape of these UAVs can imitate predators (Wang *et al.*, 2017; Egan *et al.*, 2020).
- avoid habituation by allowing feedback through the interpretation of visual or even audible signals. The coupling of an optical sensor and a nanocomputer with a detection algorithm should eventually allow the development of reactive scaring devices that are triggered only in the presence of birds. The Carnot Plant2Pro® C3-PO project plans to test this technological concept. Automatic improvement of the scaring signals by means of reinforcement learning algorithms (the algorithm evaluates the effectiveness of the signals and improves them) is also possible. Lower component prices could make these devices competitive in the future.

4.3.3 Physical protection

Protection at sowing by crop protection veil or at maturity by nets is possible in an experimental context, but this option is not economically viable in field crops.

4.3.4 Agronomy

The agronomic measures to prevent damage mainly concern those at the emergence stage. Sowing sunflower in cover crops can make it difficult to detect. This concept has been tested since 2016 by Terres Inovia and several other French organizations but the results have not yet been published. Faba beans or barley are approximately sown two months before sunflower and then destroyed with glyphosate when sowing the crop. No special equipment is required for sowing. The difficulty lies in finding the right compromise between the protective effect and the risk of competition with the sunflower crop, especially in dry conditions. These techniques are still being tested to confirm their value under a variety of conditions. However, their complexity compared to conventional practices makes them unlikely to be widely adopted by farmers.

The exploitation of a long intercropping period (*i.e.* the cover crop is sown during the previous autumn) is also envisaged, in a more prospective way, as part of a global approach integrating erosion control and fertility objectives. The absence of deep tillage, which is delicate on sunflowers, and the difficulty in finding mechanical alternatives to the possible glyphosate ban make these lines difficult to develop. Another technique mentioned in Argentina is the use of straws from the preceding cereal as spikes limiting the landing and movement of birds (pers. comm. S. Canavelli). The application of this practice in the French context is made difficult by the regulatory obligation of covering the soil during winter, and the unavoidable use of direct seeding techniques which are not well adapted for sunflower. Light harrowing after sowing, which is intended to cover seeding lines and disrupt the search for seeds, is also being investigated. No references are currently available. This technique presents few constraints for the farmer provided that the equipment is adapted to avoid the risk of crusting. At maturity, the use of desiccants is proposed by Linz *et al.* (2011) to speed up harvesting and thus shorten the phase of sensitivity to damage.

4.3.5 Varietal selection

Varieties discouraging attacks at maturity were developed in the USA in the 1980s but proved not to be effective enough, as they have a thick shell that is incompatible with the economic value of the seed (Linz *et al.*, 2011). Finally, certain morphological characteristics of the flower head can make achenes more difficult to access. Khaleghizadeh (2011) thus identified characteristics correlated with less damage, in particular a large diameter, a flat and convex shape and bending towards the ground. Varieties rich in chlorogenic acid, which is a member of the cinnamic acid family, would prevent damage according to Douville de Franssu (1997).

Varieties with high “vigour at emergence” would in principle shorten the damage susceptibility phase. This notion combines the notions of growth and development. However, there is no evidence of any genetic variability in these traits.

4.4 The promises of territorial management

There are two problems with localised control at the field scale: if the surrounding fields are not subject to any protection measures, attacks will be transferred to them. If all the surrounding fields are subject to the same protection measure, the birds will be able to tolerate the disturbance and adjust their consumption to their needs. To counter these effects, two strategies are theoretically possible (Fig. 4): the first relates to the coordination of sowing, and the second to the management of habitats, both cultivated and uncultivated, and of populations.

The synchronisation of sowing on landscapes may help to reduce the duration of the sensitive phase at maturity (Linz and Hanzel, 2015; Klug, 2017) as well as at emergence. How can we move from a recommendation to a real coordination strategy? This could be a decentralised coordination through peer-to-peer exchange of information on sowing intentions, or a centralised coordination under the supervision of one or more advisory bodies. Digital tools exist to facilitate these tasks.

Habitat and population management encompasses several types of actions. Reducing pressure on sunflowers with non-lethal methods can be achieved by moving the birds (attraction/repulsion) or the crop. This approach is for the moment rather conceptual as it raises important practical problems. However, some results have been obtained in the USA as shown below.

Birds can be driven out of crop areas in a number of ways. The destruction of favourable landscape features close to crops (roosting, nesting areas) is one of them. The destruction of *Typha* formations with glyphosate has thus had some effectiveness in the USA (Linz and Homan, 2011), while at the same time it contributes in controlling a plant species considered locally as invasive and detrimental to water birds. Another strategy could be to favour landscape elements that cause concern and discomfort (“landscape of fear”), provided that the necessary studies have been carried out. More directly, it may be possible to encourage the arrival and reproduction of predators that will take among the population or at least give the birds sufficient concern to limit their depredation. Wood pigeon predators are few in France (carrion crows in nests, peregrine falcon *Falco peregrinus*, northern goshawks *Accipiter gentilis*), but other less powerful birds of prey like the common buzzard (*Buteo buteo)* could worry them. This remains to be evaluated for extensive crops, although successful experiments have been carried for orchards (Lindell *et al.*, 2018). In practice, the aim would be to preserve or favour habitats favourable to these species and/or to install perches, with a preliminary study of landscapes and communities to optimise the system and avoid possible counter-productive effects. The falconer’s services make it possible to guarantee rapid “shock and awe”. They are expensive but effective if we rely on the feedback from one of our experimental stations near Toulouse. The falconer first carries out a diagnosis of the environment of all the fields to be protected in order to define the most suitable strategy (raptor species and scaring technique, itinerary, frequency, etc.). Biomimetic drones (Wang *et al.*, 2017) can now replace raptors, but the approach remains the same. Another method of displacing intruders is to take advantage of the aggressive behaviour of certain species towards their congeners. For example, pairs of carrion crows exclude their conspecifics in an area of several hectares around the nest. Protecting the nests or encouraging their presence helps to protect neighbouring crops from juvenile flocks. This counter-intuitive method is proposed in Switzerland (Schmid, 2012). It only applies to carrion crows. To our knowledge, no evaluation of this method has been carried out.

Attracting birds by sowing strips or spreading seed is another way to distract birds from crops. Hagy *et al.* (2008) tested the effect of 8 ha “sunflower fields for wildlife conservation” placed near *Typha* marshes to distract blackbirds. In their review, Linz *et al.* (2011) consider that this

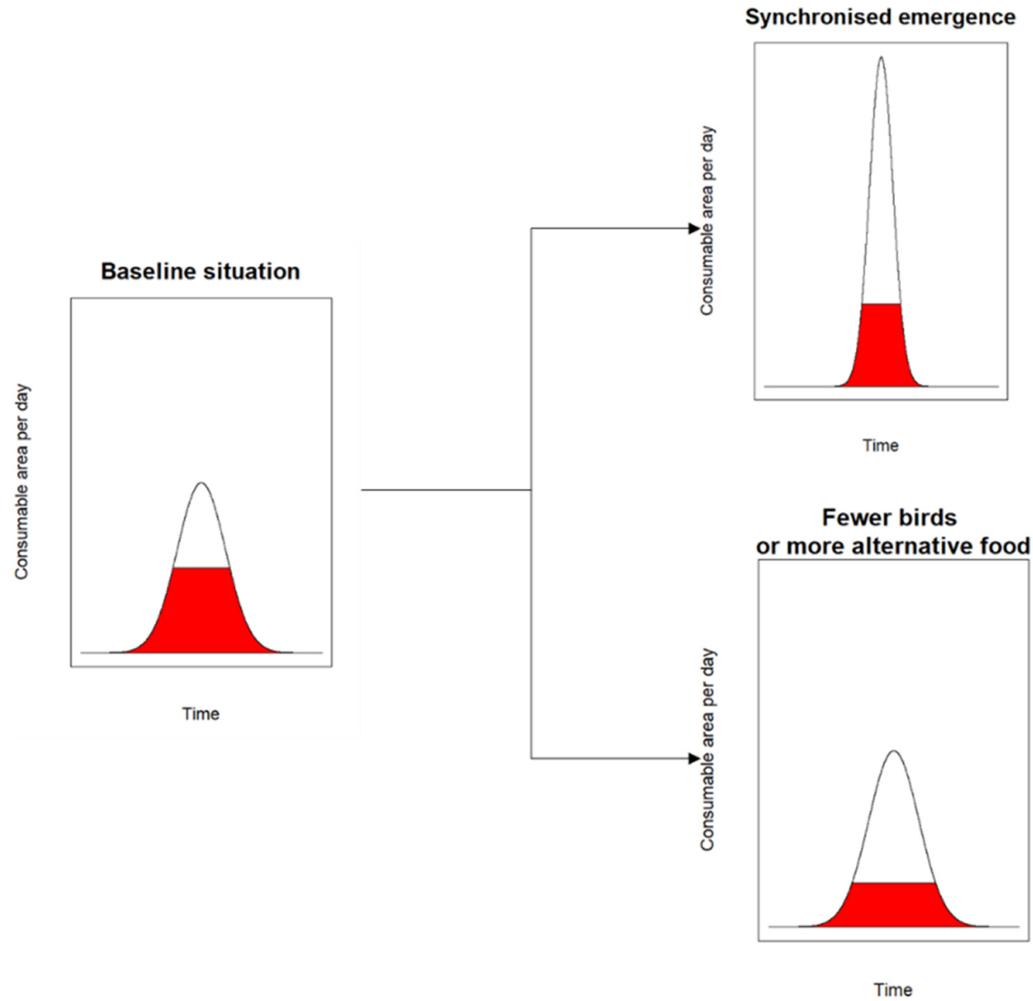

Fig. 4. Theoretical strategies for territorial prevention. The curve represents the evolution of sunflower surface at the consumable stage. The red surface represents the proportion of this surface consumed by a given number of birds. The first (top) strategy is to coordinate seedlings to provide a sunflower surface that goes far beyond bird consumption. The second (bottom) strategy is to reduce the pressure of predation by offering alternative resources, cultivated or not, or by reducing the population. The stability of bird consumption is hypothetical.

method offers a return on investment only when protecting high-value confectionery sunflowers. The same authors propose to reduce costs by using perennial sunflower varieties which also have the advantage of better erosion protection around wetlands. Nevertheless, it opens up new avenues for thinking about imagining multifunctional "agro-ecological infrastructures". Combining repulsive actions on the field to be protected with the development of attractive spaces, according to the "push pull" concept known in the case of insect control, seems a promising way forward. If these methods seem too complex, it may be simpler to avoid sowing crops in risk areas such as near *Typha* swamps, as proposed in the American reviews, or close to some urban areas or woodlands in Europe, based on farmers' local experience. However, this strategy may pose practical problems (no mapping of risk areas and constraints on rotations).

4.5 For an integrated approach

The generalist reviews cited in the Table 3 agree on the value of mixing solutions with partial effectiveness at the scale of field and territory, without however promising a miracle. That of Linz and Hanzel (2015) illustrates this idea with the different methods applicable in the Great Plains that we mentioned above: according to the authors, the winning formula consists in combining elimination of favourable habitats, acceleration of maturity with desiccants and attractive or decoy sunflower plots. The situation there seems at first glance to be more favourable than in France, where the coordination is complicated by a larger number of growers (Fig. 5). The use of glyphosate to destroy blackbird roosting habitat such as wetland *Typha* reed (Linz and Homan, 2011) beds does not raise the objections it might encounter in Europe.

Fig. 5. Landscapes of The Dakota (USA – "Prairie Basin Region") and the Gers (France) of the same size (9300 ha). The American landscape is perfectly readable: it is dominated by crops with some depressions resulting from the last glacial retreat, which are all refuges for blackbirds. The French landscape is much more complex with nested fields trees and housings. A perfect habitat mosaic for wood pigeons.

The regulatory and technical possibilities for spraying repellents on sunflower heads are greater than in Europe (authorised products, aerial applications). Finally, producers in some states benefit from government support through the distribution of scaring equipment and scientific and technical support. Nevertheless, the principles of such an integrated and territorial approach are universal. This requires adapting practices to geographical contexts and solving several problems before reaching operational solutions.

The first problem is coordination. How to coordinate various stakeholders around complex subjects? North American actions highlight an important role for the public administration (different agencies at the federal and state levels), while the French case is closer to co-management, with the Departmental Hunting and Wildlife Commissions organizing the representation of hunting, agriculture, and environmental protection sectors. These approaches remain centralized. It is not excluded that in the future digital technologies will encourage the exchange of information and "horizontal" peer-to-peer coordination. This does not necessarily have to be limited to agricultural areas. The French case argues in favour of involving the urban sector in the management of these species. Moreover, the actions undertaken must also be consistent with other objectives. An action plan to prevent bird damage must take into account hunting and environmental protection policies. Coherence must also be sought for the agricultural sector. We have seen that blackbirds provide a service for regulating maize pests. This advocates in favour of actions to displace bird populations rather than to cull them through lethal means.

From a practical point of view, how can information be collected and shared to steer territorial actions and ensure feedback? In order to establish a diagnosis and verify that actions are effective, data on damage must be compared with data on birds and management practices, as well as with context variables such as landscapes. Voluntary reporting systems alone do not make it possible to measure changes, so it is necessary to use substantial sampling systems to take into account the high heterogeneity of attacks. The contributions of digital and geographic information are of invaluable help.

Another idea, suggested by the distribution of damage concerning few producers but with increased severity, would be to resort to insurance. We did not find any evidence of this possibility in the case of sunflower, but it is mentioned in the case of rice, for example, as a potentially relevant solution from an economic point of view de Mey *et al.* (2012).

5 Conclusions

This review is not the first one. Many have preceded it by posing the problem in terms of scientific ecology, and listing the available solutions, but without being able to produce much evidence of effectiveness, except for a few local practices. We agree with their conclusions.

Bird damage is a concern for all sunflower growers around the world. Their impressive and unpredictable nature and the lack of an effective prevention method make them a dreaded calamity. Our overview has shown the complexity of this issue, which must be tackled directly at supra-field levels which are unusual for agronomists. Ecology provides us with theoretical frameworks for working on this subject, but little knowledge is currently available that can quickly be used to provide a solution to producers, at least outside the North American context. "So we are reduced to empirical methods and we should not be surprised at the failures they encounter" said agronomists in 1967 (Collective, 1967). The ideas are numerous, but without a guide to sort them out *a priori*, the tests are likely to be particularly expensive.

What research strategy should be adopted? The spatial variability of damage at different scales (field, landscape, region) and the complexity of the biological processes involved are a challenge for agronomists. The behavioural adaptation of birds is even more destabilizing because it can cause responses to vary over time. But it could also be a lever, insofar as birds can be conditioned. From this point of view, bird damage is an extreme case for agronomy, which illustrates the methodological challenges posed by the development of agro-ecology. This review and the reflections in progress to submit projects suggest two types of approaches that are intended to be coupled:

Network testing approach: screenings under controlled conditions (*e.g.* aviaries) enable the selection of methods that can be tested in the field on a few trials (technical feasibility and effectiveness) and then tested with a wider network of farmers (confirmation and effectiveness conditions; pre-development). Numerical tools and open data offer the opportunity to equip this type of strip trial system at a lower cost (Kyveryga *et al.*, 2018; Laurent *et al.*, 2019) and to control environmental variables, today landscape and weather and tomorrow bird numbers on the fields;

Territorial approach: observatories collecting local expertise and linking localized information on populations, damage and practices make it possible to produce knowledge, and secondly to monitor the effectiveness of territorial strategies coordinating actions at several levels (field, farm, landscape, region). This type of multi-scale approach has for example been tested in the case of a damaging bird on the island of Réunion (Clergeau *et al.*, 2002).

Generally speaking, the methodological stakes and the lack of organisation of research on this theme argue in favour of the constitution of networks allowing to share knowledge and experience feedback in a multidisciplinary framework associating agronomists, ecologists and socio-economists. In order to be effective and combine sufficient resources, this approach must encompass all the production sectors concerned, of which sunflower is only one part.

Our review has also highlighted a remarkable phenomenon: the damage that was once confined to sunflower maturity is now becoming more visible at emergence, at least in Western Europe. This worrying development is probably indicative of global changes operating over the long term, integrating the effects of climate change in agricultural practices and landscapes on the biotic community It implies a proactive attitude, attentive to weak signals, for diagnosis and search for solutions.

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