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DE CONSERVACIÓ DELS
POL·LINITZADORS
SILVESTRES DE CATALUNYA

WILD POLLINATORS IN CATALONIA

Report on status, threats and priority areas of action for their conservation

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Report on status, threats and priority areas of action for their conservation

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Cover photography

Top to bottom, left to right. (01) *Amegilla quadrifasciata* (Hymenoptera, Apidae), (02) *Callicera* sp. (Diptera, Syrphidae), (03) *Zerynthia rumina* (Lepidoptera, Papilionidae), (04) *Mediimorda bipunctata* (Coleoptera, Mordellidae). Authors: N. Vicens (01, 02, 04), M. A. Fuentes (03).

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Anthophora bimaculata, Hymenoptera: Apidae.(Photograph: N. Vicens).

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INTRODUCTION

Insect pollinators are critical in the correct functioning of terrestrial ecosystems. Nearly 90% of flowering plants worldwide depend on insects to transfer pollen and ensure their sexual reproduction. Pollination is therefore a key ecological process which forms the basis for the production of essential resources for a multitude of species and plays a vital role in forming many of the habitats and natural landscapes we know and love.

Furthermore, insect pollination is critical for agriculture and, therefore, for the food of the human population. 75% of the leading crops grown around the world rely on insects to guarantee the yield, quality or stability of their harvests, bestowing an extremely noteworthy economic significance on them that is, however, inadequately considered on the balance sheets of this activity. In 2016, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) published an extensive assessment of the global decline of wild pollinators and its effects on pollination and food production, placing the annual market value of global crop pollination at 235–577 billion dollars [1]. Along these lines, a review of 90 studies conducted on 1,400 crop fields in countries from five continents concludes that the contribution of wild bees to the production of insect-pollinated crops exceeds 3,000 dollars per hectare and per year [2]. The value of insects as crop pollinators, however, extends beyond the economic benefits. Insect-pollinated crops give variety to our diet, providing us with essential nutrients to maintain good health and, in short, contributing to our well-being. Given the importance of the services they provide, insect pollinators are also flagship species, enjoying a certain amount of popularity and often being considered indicators to assess the environmental quality of our natural surroundings.

Scientific evidence shows that the abundance and diversity of these insects has undergone significant declines throughout the 20th century, leading different authorities to implement pollinator conservation plans over recent years. Particularly of note among these initiatives, given its territorial relevance, is the Pollinator initiative of the European Union [3] and the Pollinator Protection Strategic Plan of the United States [4]. Moreover, different European countries and regions, such as Germany, Great Britain, Wales, Ireland, Scotland, Belgium, the Netherlands and France, have produced specific conservation strategies to halt the pollinator decline. In Spain, the *Ministry for Ecological Transition and Demographic Challenge* recently approved the National Strategy for the Conservation of Pollinators [5], which includes a diagnosis of the situation and trends of pollinators and the principal causes for their decline in Spain.

In terms of Catalonia, the Natural Heritage and Biodiversity Strategy of Catalonia 2030, the roadmap of the Government of Catalonia to halt biodiversity loss, foresees the drafting of an Intersectoral Plan for the Conservation of Wild Pollinators in Catalonia (action line 35) to address the decline of these insects. In accordance with the Strategy, the Plan must be promoted considering the results of the IPBES report. The objective of the Plan is to guarantee the conservation of wild pollinators and to maintain the functionality and productivity of agricultural ecosystems through a series of actions aimed, among others, at recovering multi-functional margins, benefiting useful fauna for the crops and spreading the services and benefits that wild pollinators provide. Despite this, the approval and publication of the National Strategy for the Conservation of Pollinators and the new EU Biodiversity Strategy for 2030 mean that the Plan must be broadened and adapted to the new decisions arising from these instruments.

The objective of this report is to gather and organise the scientific information currently available to produce and deploy the Intersectoral Plan for the conservation of wild pollinators in Catalonia. The problems surrounding pollinator declines are extensive and complex, which has determined the structure and contents of this report.

The report consists of two very different parts. Part one contains a **diagnosis** of the importance of pollination and of pollinators; an analysis of the status and population trends of pollinators; the identification and description of the causes of the declines and the consequences on wild plant and crop pollination; an analysis of the relationship between pollinators and agriculture, in terms of both the ecosystem service of pollination and intensive agriculture as a key factor in pollinator decline; and finally, a chapter on the challenges and improvements in knowledge that must be addressed in order to progress in the search for solutions. An overview of the situation of wild pollinators around the world and in Europe is introduced throughout this first part, along with a view that focuses on Catalonia in order to identify gaps in pollinator knowledge in Catalonia. Each chapter includes a section of the corresponding scientific and technical **bibliographic citations**. Part one ends with a chapter on the main conclusions and key messages that can be taken from the diagnosis.

The second part of the document identifies the **priority areas** on which the activities of the Intersectoral plan for the conservation of wild pollinators should focus, based on the diagnosis and analysis of the national and international strategic planning instruments currently in force. Some of the **measures** which could be considered in the Plan are also proposed, considering the main factors of risk and threat to pollinators and the opportunities and favourable synergies that might exist in the specific context of Catalonia.

1. IPBES. 2016 The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production.
2. Kleijn D *et al.* 2015 Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. Nat. Commun. 6, 7414. (doi:10.1038/ncomms8414)
3. European Comission. 2018 EU Pollinators Initiative. See https://ec.europa.eu/environment/nature/conservation/species/pollinators/policy_en.htm.
4. EPA. 2008 Pollinator Protection Strategic Plan. See https://www.epa.gov/pollinator-protection/pollinator-protection-strategic-plan.
5. MITECO. 2020 Estrategia Nacional para la Conservación de los Polinizadores. See https://www.miteco.gob.es/es/biodiversidad/publicaciones/estrategiaconservacionpolinizadores_tcm30-512188.pdf.

PART ONE

DIAGNOSIS

The sooty orange tip, *Zegris eupheme*, a highly threatened butterfly in Catalonia.
(Photograph: Jana Marco Tresserras).

CHAPTER 1
THE IMPORTANCE OF POLLINATION AND OF POLLINATORS

1.1 POLLINATION AND THE REPRODUCTIVE SYSTEMS OF PLANTS

Pollination is a key process in the **sexual reproduction of plants**. It consists of grains of pollen being transferred from the anthers of a flower (male part) to a stigma (female part). Once it has landed on the stigma, the pollen grain develops a pollen tube through which the male gametes travel to the ovary where they fuse with the ovule (fertilisation), leading to the formation of the seed and the fruit (Fig. 1).

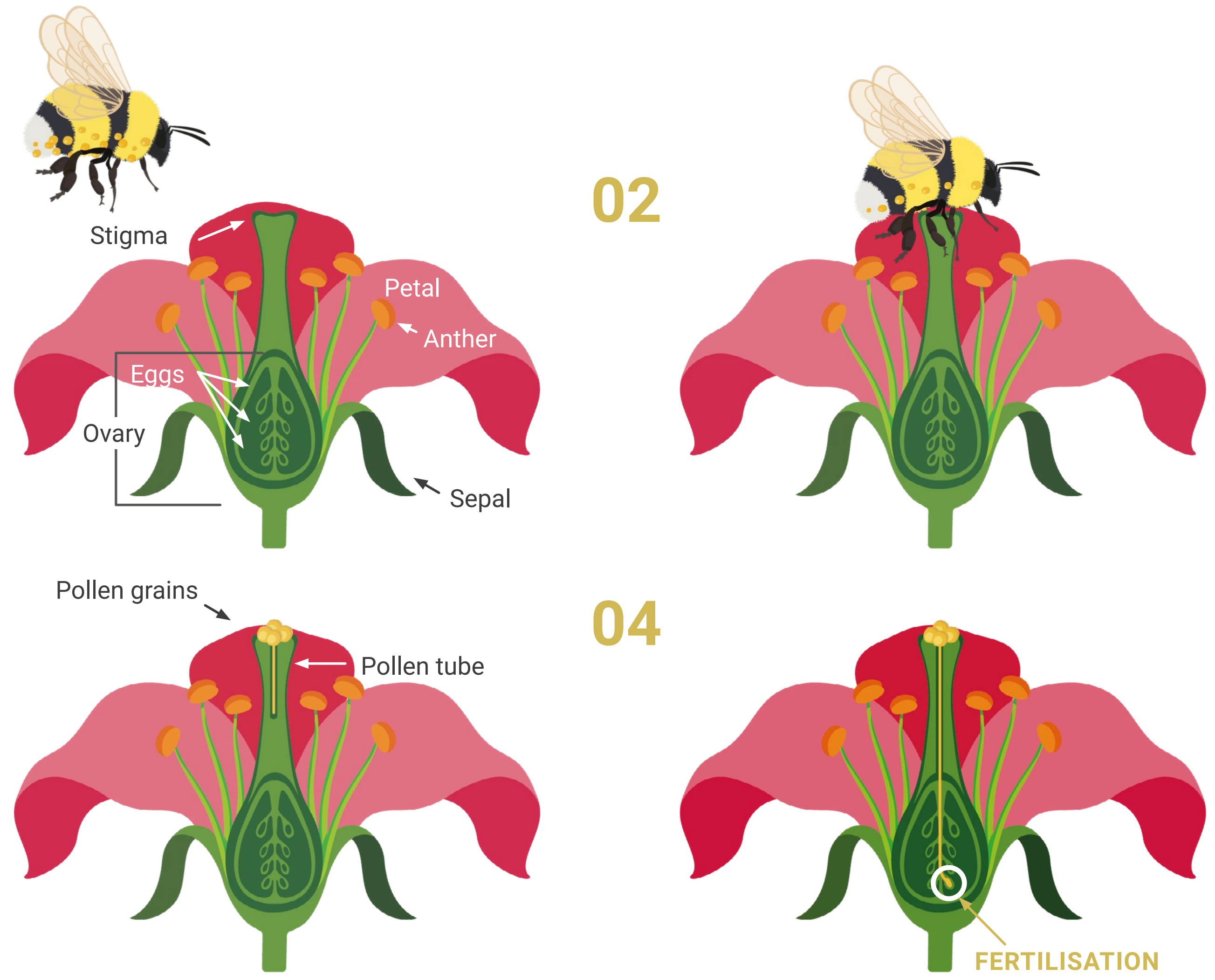

Fig. 1. Schematic representation of the pollination and fertilisation process of a flower. (01) Arrival of a pollinator carrying pollen; (02) depositing of pollen grains on the stigma; (03) germination of the pollen grains and formation of the pollen tube; (04) fertilisation of the egg.

Pollen is transferred in different ways. In some plants, such as pines, oaks, holm oaks and cereals, pollen is carried by the wind. In others, which generally have attractive flowers, pollen is transferred by certain groups of animals, including insects (**entomophily**). Lastly, in a small group of plants, pollen is displaced by water.

Regardless of the manner in which it is transferred, there are different types of pollination, depending on the source of the pollen. It is normally transferred between plants of the same species (conspecific **pollination**). Sometimes, however, it is transferred between individuals of different species (**heterospecific pollination**). Heterospecific pollination between very close species can lead to hybrids although, as a general rule, fertilisation does not occur when the male gametes and the ovule are from different species. Within conspecific pollination, self-pollination is when the pollen deposited on the stigma comes from the same flower or from another flower on the same plant. The fertilisation process arising from these two types of self-pollination are called autogamy and geitonogamy, respectively. Genetically speaking, autogamy and geitonogamy are the same, and can be grouped together under the term "self-fertilisation". When the pollen comes from a flower on another plant, this is known as cross-pollination. The resulting fertilisation, called allogamy or xenogamy, involves the combination of genetic material from two different plants.

Many plants (known as **self-compatible** or self-fertile) can be fertilised and form viable seeds through both self-fertilisation and xenogamy, although seeds fertilised through xenogamy are often more viable. In other plants, known as self-incompatible, xenogamy is obligate, which means they only form fruit and seeds if the pollen comes from a genetically different plant.

1.2 FRUIT AND SEED FORMATION

Pollen grains deposited on a stigma germinate and develop a pollen tube which grows until it reaches the ovary (Fig. 1). Two male gametes travel along this pollen tube. One of them fertilises the egg cell in the ovule to form a zygote, which becomes the embryo. The other gamete fuses with the so-called polars nucleii of the ovule to form a nutritious tissue (secondary endosperm), which protects and feeds the growing embryo. The embryo and the endosperm together form the **seed**, which has the capacity to form a new plant. Alongside fertilisation, the other tissues of the ovary are transformed into **fruit**, which protects the seeds and is often involved in their dispersal. In many plants, the ovaries contain more than one ovule and, therefore, may contain many different seeds.

Pollination is an essential yet, in itself, insufficient step in fruit formation. A correctly pollinated flower will only yield fruit if it receives enough resources in the form of **water and nutrients**. Therefore, a low fruit yield may be due to inadequate or insufficient pollination or other causes. Two measurements are used to assess the fruiting of a plant. One, known as **fruiting percentage**, is the proportion of flowers that ultimately form fruit.

This measurement is related to the number of flower that have been pollinated. The other measurement is the **number of seeds formed per fruit**, which is related to the number of pollen grains deposited in the flower.

Even in optimum conditions, only a fraction of all flowers ultimately produce fruit. It is therefore important to know whether fruit and seed production in a population of wild plants or in cropland is limited by pollination or by other factors. To answer this question, a comparison must be made between the fruiting percentage and the number of seeds per fruit among flower pollinated naturally by pollinators and flowers pollinated by hand using compatible pollen. This latter group of flowers provides a measurement of the maximum yield the plant is able to produce when pollination is not a limiting factor. If the production values of naturally pollinated flowers are significantly lower than those of hand-pollinated flowers, this means that production is limited by insufficient pollination. This situation normally arises in cropland and areas where pollinators are scarce, or in adverse weather conditions for pollinator activity. In these cases, measures must be taken to correct the **pollination deficit** (Chapter 5). In addition to the quantity of pollen grains deposited, seed production may also be limited by the "genetic quality" of the deposited pollen [1]. For example, as explained previously, embryos from eggs fertilised through autogamy might be less likely to survive.

1.3 POLLINATORS

The lives of different animal groups is closely linked to flowers. Most of these so-called **flower-visiting** animals call on flowers to obtain food, primarily pollen and nectar and occasionally floral oils. During their visits, these animals may inadvertently transfer pollen to the stigma of the flowers and, therefore, act as pollinators. Other animals visit the flowers for shelter or warmth, to mate or to prey on other flower visitors. In general, they are not overly effective pollinators, despite being occasionally able to transfer pollen.

In tropical regions (and sometimes in island systems), certain groups of reptiles (lizards), birds (such as hummingbirds) and mammals (some bats and primates) are important pollinators of some plants. In general, however, the main pollinators of most plants worldwide and particularly in Europe are insects [2]. The insect orders with most pollinator groups are Coleoptera, Lepidoptera, Diptera and Hymenoptera. Some Heteroptera, Orthoptera and Dictyoptera also visit flowers more or less occasionally, although they play a much more minor role as pollinators.

1.3.1 Coleoptera (beetles)

The Order **Coleoptera** includes different families with species that, in their adult stage, feed primarily on pollen and nectar (Fig. 2). It is estimated that there are around 750 species of Coleoptera in the Iberian Peninsula that can clearly be considered flower visitors [3].

Unlike other groups of insect pollinators, which have specialised, tongue-like structures in their mouths, the mouthparts of adult Coleoptera are adapted for chewing. The larvae feed on products of non-floral origin, such as wood, seeds or other plant materials.

Coleoptera particularly visit open flowers, where nectar and pollen is easily accessible. Coleoptera generally spend a long time visiting each flower, which means that they visit only a few flowers per time unit. Furthermore, in some cases they feed partially on the petals and other organs of the flower, which is why the pollinating contribution of Coleoptera is considered relatively low. On all accounts, in some cases their pollination effectiveness (number of pollen grains deposited per visit) is extremely high [4], becoming greatly abundant in Mediterranean environments, thus offsetting their low number of visits.

Fig. 2. Coleoptera. (**01**) Two male *Oedemera nobilis* (Oedemeridae) on a chicory flower, *Cichorium intybus*, and (**02**) a female *Anthaxia hungarica* (Buprestidae) on an andryala flower, *Andryala integrifolia*. (Photographs: N. Vicens).

1.3.2 Lepidoptera (butterflies and moths)

The Order **Lepidoptera** is divided into two large groups, Rhopalocera and Heterocera. Rhopalocera (**diurnal butterflies**) include around 230 species in the Iberian Peninsula, distributed over 6 families. Heterocera (**moths or nocturnal butterflies**) including around 4800 species in the Iberian Peninsula, although many do not act as pollinators because they do not feed on flowering plants [3]. Most are nocturnal, yet some have day-time habits.

All adult flower-visiting Lepidoptera feed on nectar. They have a tongue, known as a proboscis because it remains wound in a coil, which can be extremely long and is used to imbibe the nectar. The females place their eggs on leaves and other parts of plants which the larvae (caterpillar) feed on. The diet of the larvae is often rather specialised, and is restricted to only a few plant species.

Despite visiting all types of flowers, butterflies have a certain preference for rose flowers and lilies with deep corolla tubes. Moths from the **Sphingidae** family particularly visit large flowers that produce a lot of nectar. Other groups of moths especially visit flowers in soft colours and/or heavily aromatic flowers. Given the length of the proboscis, there is often little contact between the butterfly's body and the reproductive organs of the flowers. Lepidotera are therefore often considered relatively ineffective pollinators in comparison with other groups. Despite this, they can be significant pollinators of plants with deep corolla tubes. For examples, some butterflies pollinate the martagon lily (*Lillium martagon*) [5]. In this case, pollination involves the pollen that the butterflies carry stuck to their wings, in a process known as wing pollination. Some plants, the flowers of which open during the night, are mostly pollinated by Sphingidae. Unlike other groups of pollinators, Lepidoptera often fly long distances between flowers visited consecutively. This enables them to promote cross-pollination between distant plants and, therefore, favours exogamy [6,7].

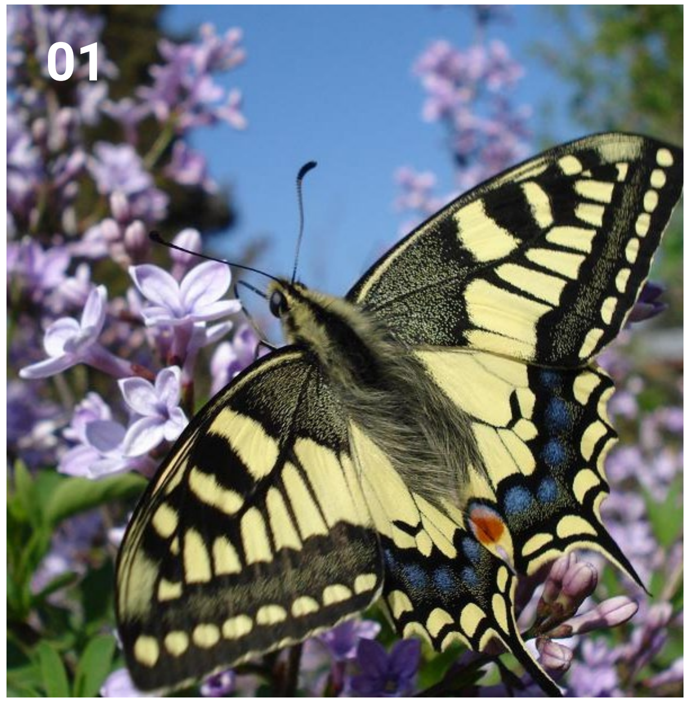

Fig. 3. Lepidoptera. (**01**) An Old World swallowtail (*Papilio machaon*; Papilionidae) sucking on a lilac flower (Syringa persica); (**02**) Mating of the black-eyed blue (*Glaucopsyche melanops*; *Lycaenidae*), a species in strong regression in Catalonia (Photographs: A. Arrizabalaga; M. A. Fuentes).

1.3.3 Diptera (flies and mosquitoes)

The Order Diptera is divided into two suborders, Nematocera (mosquitoes and similar) and Brachycera (flies and similar). This very large group includes over 6400 species in the Iberian Peninsula [8]. Nematocera rarely visit flowers. Brachycera, however, include some eminently flower-visiting families, such as Syrphidae (around 400 species in the Iberian Peninsula) and Bombyliidae (close to 200 species). Most Syrphidae and some Bombyliidae look like bees or wasps, and often hover. Other families, commonly known as "flies", also include species that regularly visit flowers [3].

Flower-visiting diptera feed on nectar and pollen, and can play a very important role in pollination [9,10]. Their tube-shaped mouthparts enable them to suck up nectar and can be rather long in some Bombyliidae.

Fig. 4. Diptera. (**01**) A female *Sphaerophoria scripta* (Syrphidae) visiting a dusty mullein flower, *Verbascum pulverulentum*; (**02**) a female *Eristalis tenax* (Syrphidae) visiting a cherry plum flower, *Prunus cerasifera*; (**03**) a male *Bombylella atra* (Bombyliidae) visiting a daisy flower, *Bellis perennis*. (Photographs: N. Vicens).

Furthermore, many flies visit flowers for shelter at night-time or for warmth. The diet of flower-visiting diptera larvae does not include flowering plants. Many feed on excrements and other types of decomposing organic matter. Others are parasitoids of other insects. The larvae of many Syrphidae are aphid predators, which means they play an important role in the biological control of agricultural systems.

Diptera prefer light-coloured flowers (white, yellow) with shallow corolla tubes and easily accessible pollen and nectar. They are sometimes the most numerous visitor of these plant species (in many umbelliferae, for example), and their pollination effectiveness can be relatively high, especially among syrphids [4]. Some long-proboscis Bombyliidae frequently visit corolla tube flowers. The role of diptera as pollinators is particularly important in mountain habitats, where bees are scarcer [11,12].

1.3.4 Hymenoptera (wasps, ants and bees)

Hymenoptera are an extremely diverse order that includes what are commonly called wasps, ants and bees. It includes a total of 9000 species in the Iberian Peninsula. Although the terms "ant" and "bee" correspond to well established, monophyletic groups, the term "wasp" applies to different groups with little relationship between them, making them difficult to define. Traditionally, the order Hymenoptera can be divided into three major groups, Symphyta (herbivore wasps), Parasitoida (which includes parasitoid wasps and gall wasps) and Aculeata (which includes ants, bees, predatory wasps and some parasitoid wasps) [2].

Symphyta include several families, the larvae of which feed on plant tissue. These are known as "sawflies" due to the shape of their ovipositor. Unlike the other Hymenoperta, they have no constriction between the functional thorax and the gaster (functional abdomen), which is why they are called "waistless wasps". The adults of this species feed on nectar and pollen, and also sometimes on small insects. Some species have a certain degree of specialisation towards certain plant species, and they can play a significant role as pollinators [3].

Parasitica are an extremely diverse group formed particularly of parasitoid wasps. The females place their eggs on insects and arachnoids, which serve as food for the larvae. Most are small-sized species. The adults of some families occasionally visit flowers to feed on nectar. Generally speaking, given their small body and their infrequent visits, these wasps play a relatively insignificant role as pollinators. An important exception is the *Blastophaga psenes* species from the Agaonidae family, which is the only pollinator of wild fig trees (*Ficus carica*).

Aculeata are characterised by the modification of their ovipositor into a stinger which they use for attack and/or defence. These include ants, bees, and different families of wasps. All **ants** (around 300 species in the Iberian Peninsula) are social, which means they live in societies made up of one or more queens (fertile females) and a great many workers (sterile females). The workers of different species (particularly from the Formicinae subfamily) collect nectar and can even be plentiful on some flowers. The diet of the larvae is extremely varied and can be carnivore (insects and other arthropods) or herbivore (seeds and other plant products), depending on the species. Ants especially visit flowers with accessible nectaries. Because of their small size, they often enter nectaries without touching the reproductive organs of the flower, acting as "nectar thieves". Despite this, they can play a significant role as pollinators on some plants [3].

Aculeata include different families of **wasps** that can be predatory or parasitoid, the adults of which feed on nectar from flowers. Predatory species build nests and provide them with prey (insects or spiders) to feed their larvae. Parasitoid species do not build nests and place their eggs directly on their hosts. Some predatory species are social although most are solitary, which means that each female rears its offspring without cooperating with other females. Within the Vespidae family, members of the Masarinae subfamily (11 species in the Iberian Peninsula) have abandoned the carnivore diet and provide their nests with pollen and nectar to feed their larvae. Like ants, wasps with stingers particularly visit relatively shallow flowers with accessible nectaries. They are rarely plentiful on flowers, although their visiting rate is much higher than that of ants, and their pollination effectiveness can be relatively high. Furthermore, the males of some species exclusively visit and pollinate certain species of orchids [3].

Bees comprise around 1100 species in the Iberian Peninsula, distributed among more than 50 genera and 6 families [13]. Some species, such as the honey bee and the bumblebee are social, although most are solitary. In both cases, the females build nests and provide them with pollen and nectar to feed their larvae. Females of this species therefore not only visit flowers to feed from the nectar but also to collect pollen and nectar for their larvae. This dependency on floral resources means that bees visit a large number of flowers, more than any other group of pollinators. Other species (know as cuckoo bees) place their eggs in the nests of other bees. The larvae of these species kill the host's egg and feed on the pollen and nectar provisions (kleptoparasitism). Adult cuckoo bees and the males of nest-building species only visit flowers to feed on their nectar. For most plant species, bees are the most importantflower

Fig. 5. Hymenoptera. (**01**) A predatory solitary wasp, *Odynerus consobrinus* (Vespidae) on thyme flowers, *Thymus vulgaris*; (**02**) a worker honey bee, *Apis mellifera* (Apidae), collecting pollen and nectar from a borage flower, *Borago officinalis*; (**03**) a male solitary bee *Hoplitis cf adunca* (Megachilidae) on sweet scabious, *Scabiosa atropurpurea*; (**04**) a kleptoparasitic bee *Thyreus cf histrionicus* (Apidae) collecting nectar from a chasteberry flower, *Vitex agnus-castus*. (Photographs: N. Vicens).

visitors [14,15]. In addition to floral resources, bee populations require appropriate nesting substrates. Most species dig nests under ground, although some nest in pre-established cavities, such as holes in dead tree trunks or hollows between rocks. A smaller number of species dig nests in dead wood substrates or in plant stems, such as bramble, and a few species build nests of mud or resin on rocks or plant life. Bumblebees often nest in abandoned rodent burrows.

1.4 INTERACTIONS BETWEEN PLANTS AND POLLINATORS

Most species of pollinators are **generalist** and visit a wide range of flowers on very diverse species. Others, however, are extremely **specialist** and only visit one or a few plant species. The degree of specialisation of a pollinator species depends on a series of factors.

In some species, the life cycle of the pollinator is closely linked to one plant species. For example, the larvae of the *Blastophaga psenes* wasp only develop on infructescences of fig trees [16]. Similarly, the larvae of the *Derelomus chamaeropsis* beetle develop exclusively on inflorescences of the Mediterranean fan palm (*Chamaerops humilis* [17]). In these cases, the pollinator only visits its host plant, where it is the only or the principal pollinator, which means complete interdependence between the plant and the pollinator. In other cases, the pollinator restricts its visits to only a few plant species. Some solitary bees, for example, only collect pollen from a single genus (monolecty) or family (oligolecty) of plants [18]. Despite this, these species can visit other plants to obtain nectar. The remaining species of bees collect pollen from different families of plants (polylecty). Although they are generalist, many pollinators show a preference for certain morphological or physiological traits in plants. Pollinators with significant food requirements (social species and large-sized species) often visit flowers that are either extremely abundant or produce large amounts of pollen and/or nectar [19,20]. Ease of access to floral resources also plays an important role in the selection of flowers visited by pollinators. There is a certain correlation between the length of the mouthparts of pollinators and the depth of the corolla tube of the flowers they visit [21–23]. Lastly, some pollinators show a preference for certain colours or smells of flowers [24,25].

Despite these preferences, the selection of flowers visited by a pollinator depends to a great extent on the floral context and on the rest of the local pollinator community. In many cases, pollinators can adapt their preference to suit the range of floral resources available, which varies in terms of both location and time. For example, a plant which is initially extremely attractive may no longer be so if it receives a large number of visits that lower its pollen and nectar levels. In short, in terms of the community, the relationship between plants and pollinators is usually rather generalist and often opportunist. In the undergrowth of El Garraf Nature Reserve, a pollinator species visits an average of 4–5 plant species, and a plant species receives visits from an average of 30–40 pollinator species [26]. These relationships form complex **interaction networks** (Fig. 6). The high level of connectivity of these networks means that a disruption, such as the extinction of a certain species or the introduction of a new one, might affect a large number of species in the community.

PLANT-POLLINATOR INTERACTION NETWORK IN THE UNDERGROWTH OF EL GARRAF NATURE RESERVE

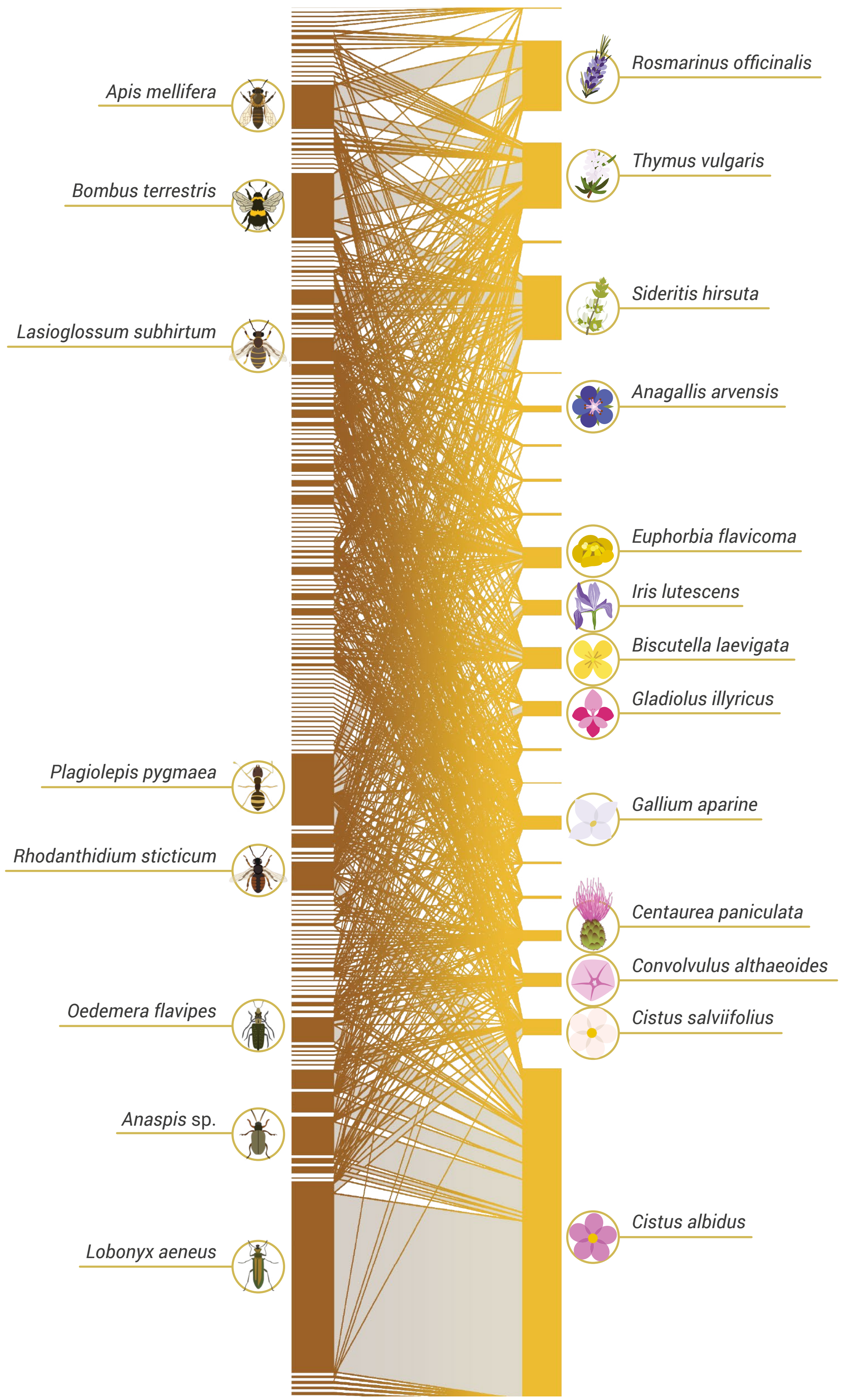

Fig. 6. Plant-pollinator interaction network in the undergrowth of El Garraf Nature Reserve. The principal 23 entomophilous plants interact with 201 species of insect pollinators to form over 900 interactions. Each species is represented by a rectangle. The height of the rectangles shows the interaction frequency of each species. Some pollinators focus most of their visits on only a few plant species, although most visit a great many plants. (Source: [26]).

1.5 POLLINATION EFFECTIVENESS AND CONTRIBUTION

Pollination effectiveness is the quantity of pollen that a pollinator deposits on the stigma (or stigmas) of a flower during one visit. A great many factors affect this effectiveness [4]. Firstly, collecting behaviour, which is the position and movements of the pollinator above the flower, is essential. In some flowers, for example, the pollinator can access the nectaries from the front or from the side. Front access guarantees contact with the anthers and the stigmas, thus favouring high levels of pollen collection and removal. Side access, however, means that the nectar can be extracted without touching the reproductive organs of the flower. One extreme example of this behaviour is that of some bees which bite the base of flowers with deep corolla tubes in order to insert their proboscis from outside and "steal the nectar" without even entering the flower [27]. Pollination effectiveness is often related to the type of resource collected. Pollinators that collect pollen are often more effective than those that collect nectar. Pollination effectiveness also depends on the visit duration. Short visits often deposit less pollen than long visits. The size of the body is another important factor, with large pollinators usually being more effective than their smaller counterparts [4].

On all accounts, the quantity of pollen a plant receives from different visiting pollinators (**pollination contribution**) does not only depend on pollination effectiveness but also on the visitation rate of each pollinator. Along these lines, a relatively ineffective pollinator can make a significant contribution if its visitation rate is high. The visitation rate of a pollinator species to a specific plant species will depend on the abundance of the pollinator population, its dependence on floral resources, and its affinity for the plant.

Pollination effectiveness has been considered in quantitative terms (pollen grains deposited on stigmas) up to this point. As explained in Section 1.2, however, seed formation may also be limited by the **quality of pollen grains** deposited on the stigma [1]. In mass flowering plants, such as trees and shrubs, some pollinators consecutively visit a great many flowers on the same individual, so that most of the pollen transferred comes from flowers from that same individual, thus favouring **autogamy** [28]. However, other pollinators visit a few flowers on each plant and, therefore, favour **cross-pollination**. In principle, the degree of kinship between two plants from the same population decreases with distance, which means that pollinators visiting only a few flowers per plant and travelling long distances between plants promote **gene flow** within a population [7].

Another important aspect is that of **floral constancy**, defined as the trend of a pollinator to consecutively visit flowers of the same species. Most pollinators show a high degree of floral constancy, thus avoiding heterospecific pollination. In some cases, however, particularly when resource availability is low, a pollinator can alternate visits between different species or visit one species to obtain pollen and another to obtain nectar. In general, heterospecific pollen deposition is of little importance, although in extreme cases it could block the stigma of the flower and hinder the germination of conspecific pollen grains [29].

1.6 POLLINATION AS A KEY PROCESS IN THE FUNCTIONING OF NATURAL ECOSYSTEMS

Pollination is a critical process for the **functioning of terrestrial** ecosystems. Almost 90% of all flowering plant species worldwide depend to some extent on pollinators for their sexual reproduction [30]. A recent study estimates that, without pollinators, half of flowering plant species would suffer an 80% or more reduction in seed production [31]. This reduction would reach 100% in one third of the species. Therefore, a general decline in pollinators would affect the reproductive success of many plants and would radically transform terrestrial ecosystems. The abundance of many plants would decrease, and some could even become extinct. This would lead to the depletion of plant communities and a dominance of species that are less dependent on pollinators, such as wind-pollinated plants or those with asexual reproduction mechanisms. It has been proven that even relatively minor changes in the abundance and composition of pollinators visiting a plant species can have a significant impact on its reproduction and demography [28]. As explained Section 1.4, plants and pollinators form closely connected interaction networks, which means that demographic changes in one single plant species could end up affecting the entire community of plants and pollinators.

Changes in the reproductive success of plants would directly affect the animals that depend on them as a source of food, particularly those feeding on fruit and seeds. The diet of different animal groups, such as many insects, including harvester ants, and many birds, is based almost exclusively on the seeds and/or the fruit from insect-pollinated plants. Seeds and fruit are not a staple in the diet of other groups of animals, such as mammals and birds, although they are important insofar as nutrition and energy are concerned, particularly during certain times of the year. Therefore, pollinators are ultimately essential in guaranteeing the stability of the **trophic network** built around plants.

1.7 POLLINATION AS A ECOSYSTEM SERVICE

Animal pollination provides an extremely important **ecosystem service** to humans, contributing decisively to **agricultural production**. 75% of the main crops around the world depend to some extent on pollination by animals, particularly insects, to produce fruit and seeds [32]. This **degree of dependence** is measured as the percentage of production that would be lost without pollinators. The crops for which pollinators are essential (90–100% degree of dependence) include cocoa, melon, watermelon, pumpkin, kiwi, and many varieties (self-incompatible) of almond tree. Other crops, such as most fruit trees, cucumber, mango or avocado, have a high (40–90%), moderate (10–40%; aubergine, strawberries) or low (10%; tomato, some citrus fruits, papaya) degree of dependence (Fig. 7). Other crops, including cereals, olives and grapes, are not dependent on insect pollination. Lastly, the degree of pollinator dependence is unknown for some crops (such as certain legumes, medlars and anise).

DEGREE OF POLLINATOR DEPENDENCE

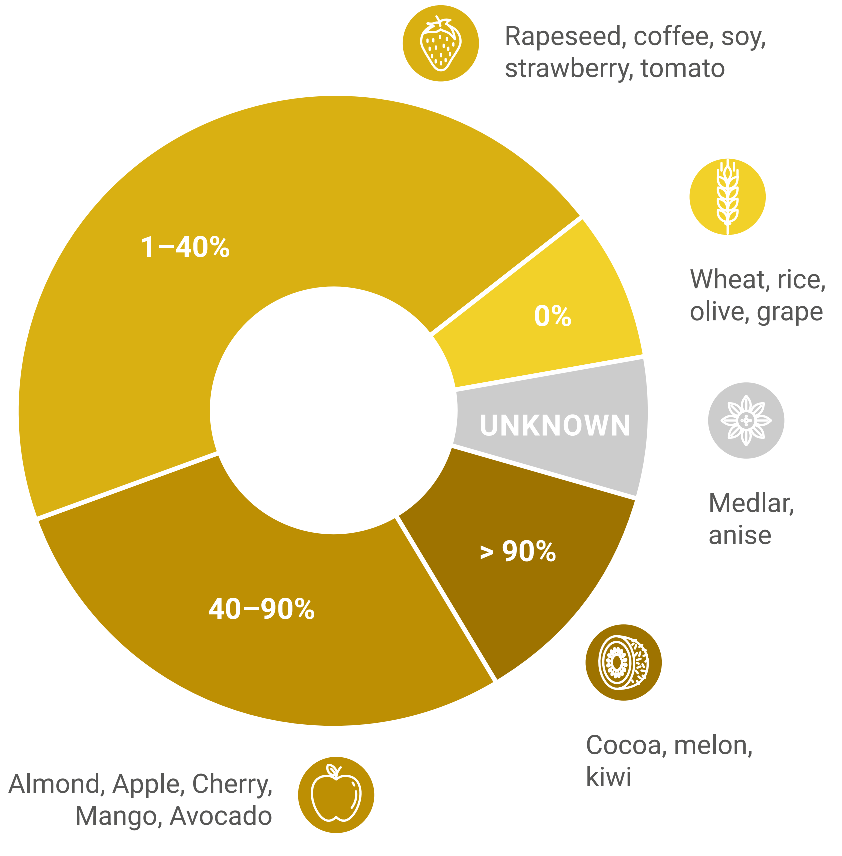

Fig. 7. Percentage of crops with different degrees of animal-pollination dependence worldwide. (Source: [32,33]).

Overall, insect-pollinated crops primarily include fruit, a great many vegetables and some nuts, along with crops of seeds used to produce oil, such as sunflower and rapeseed. The role of pollinators must also be highlighted in the production of seeds for many different forage crops, such as alfalfa or clover, and for crops that do not provide food but important materials for humans, such as cotton [34]. Worldwide, crops depending on pollinators account for 35% of global production [35]. The remainder comprise cereals and root crops (60%), which are wind-pollinated, and crops for which their degree of pollinator dependence is unknown (5%) [36]. The **economic value** of the ecosystem service of pollination worldwide is estimated at between 235 and 577 billion dollars a year [36]. The distribution of profits from animal pollination is not consistent around the world. The regions to most profit from this ecosystem service are Western Asia, the Middle East, Mediterranean Europe and North America.

In Europe, crops requiring entomophily account for 15% of production and 31% of agricultural profits [34]. There would be a 7% decrease in production without pollinators [34], with losses of over 3 billion euros a year [37]. The degree of pollination dependence in agricultural production in Catalonia and its economic value is discussed in Chapter 5.

Apart from the economic value, it is important to consider that food from insect-pollinated crops is particularly rich in micronutrients, such as vitamins, minerals and certain antioxidants (particularly fruit and vegetables), and also in lipids (oilseeds) [38]. These are essential in guaranteeing the **healthy nutrition** of human populations. From a One Health perspective, one approach which acknowledges that the health of people is closely linked to the health of the ecosystems and of the environment we share, and a decrease in these products in the human diet would lead to an increase in certain diseases and nutritional deficiencies [39,40]. Pollinators are therefore crucial in guaranteeing the food of human populations on both a quantitative and a qualitative level.

The amount of insect-pollinated crop land has increased over recent decades and, therefore, demand for the pollination service is expected to increase [41,42]. Unfortunately, in some major agricultural regions such as the United States, Brazil, Argentina and some European countries, the increase in the amount of land used for insect-pollinated crops has been accompanied by a trend towards monoculture, thus leading to a loss of biodiversity [42]. As explained in Section 1.8, pollinator diversity is essential in guaranteeing the **stability** of the pollination ecosystem service. To this end, it has been seen over the past 50 years that crops with a higher degree of pollinator dependence have a more unstable yield [43].

In short, a generalised reduction in the insect-pollination service would lead to extremely significant production losses both locally and worldwide. These losses would have an impact on the financial profits of producers and would lead to supply problems, with the consequent price increases for consumers.

1.8 THE IMPORTANCE OF DIVERSITY

The diversity of an animal or plant community refers to the richness of species (total number of species present in the community) and to the equitable distribution of the amount of different species. In other words, a community is more diverse if it has more species, but also if the amount of the different species is similar. A community is less diverse, however, when it has few species and/or when one or a few species are extremely dominant.

Diversity is important for the **functioning of ecosystems,** as diverse communities have greater capacity to withstand and recover from disturbances. This is because a greater diversity of species also means a greater diversity of biological traits or characteristics (**functional diversity**). In the event of a disturbance, whether of natural or anthropogenic origin, the more species there are in the community with different traits, the more likely it is that some of them will be able to deal with the disturbance, that the community will not collapse, and that the functioning of the ecosystem can be maintained [44,45]. Therefore, maintaining communities of different pollinators in natural, semi-natural, agro-forestry and agricultural areas guarantees greater **resistance and resilience** to disturbances such as climate change or changes in land use.

The diversity of pollinators is crucial in guaranteeing the pollination function and ensuring the persistence of plant communities [46,47]. A plant community is formed by a certain number of species, each with different morphological and functional characteristics. These differences include the bloom period, the size and shape of the flower, the depth of the corolla tube, the position of the anthers and the stigmas, and the number of pollen grains the stigmas must receive for maximum seed production. In short, the types of pollinators that can adequately pollinate a plant species depend on these characteristics, among others. There will be species in a diverse pollinator community with different flight periods, with preferences for different floral traits and types of pollen, and with different lengths of mouthparts enabling them to access shorter or deeper corolla tubes. This functional diversity of pollinators will ensure that all plant species in the community receive an adequate pollination service [48]. Ultimately, a diverse plant community can only last over time if it has an equally diverse pollinator community. Likewise, a diverse plant community will help maintain a diverse pollinator community [49].

The importance of pollinator diversity on the pollination function also becomes apparent when considering a single plant species. Some studies have shown a positive relationship between the diversity of pollinators and the production of seeds and fruit in different wild plants [50]. This relationship is particularly strong when the pollinator community includes different functional groups, such as social bees, solitary bees, and syrphids [51]. This type of relationship has also been proven in certain crops, in which the pollination service increases with the functional diversity of pollinators [52–54]. This positive effect of the functional diversity of pollinators can be explained by two mechanisms. The first is **complementarity**. Different pollinator species can have complementary traits. One pollinator might be more active in the morning and another in the afternoon, for example. Or one pollinator might prefer to visit flowers at the top of a tree while another prefers the flowers from the bottom (Fig. 8). Hence, the pollination service will be more complete when the two species coexist [49]. The second mechanism explaining the positive relationship between pollinator diversity and pollinating function is **redundancy**. In a rich pollinator community, there will be different species with similar functional traits. Pollinator populations may suffer major fluctuations from one year to the next. Redundancy means that, if a pollinator species becomes extremely scarce or even disappears, its pollinating function can be replaced by other functionally equivalent species (Fig. 9).

EXAMPLE OF FUNCTIONAL COMPLEMENTARITY

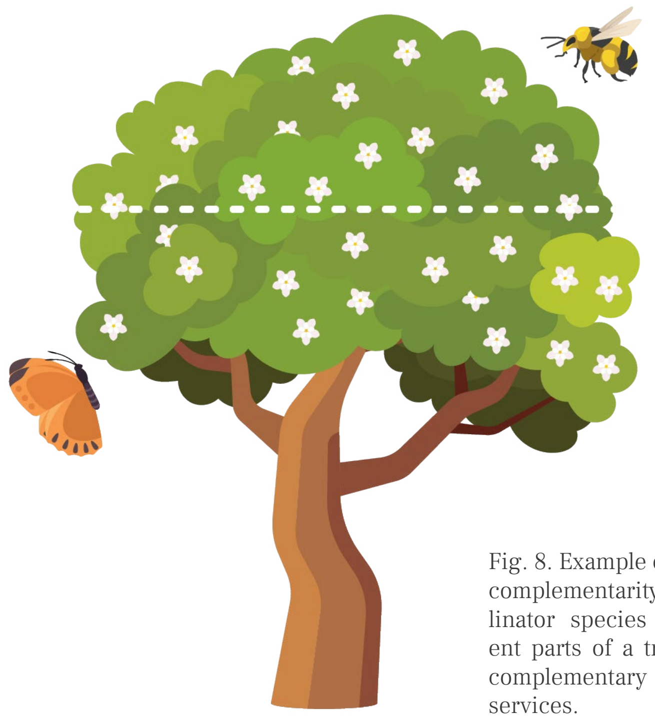

Fig. 8. Example of functional complementarity. Two pollinator species visit different parts of a tree, offering complementary pollination services.

In short, pollinator diversity is key in ensuring the correct functioning of ecosystems and in guaranteeing the crop pollination ecosystem service, thus guaranteeing the conservation of plant and pollinator communities in both natural and agricultural systems.

EXAMPLE OF FUNCTIONAL REDUNDANCY

Fig. 9. Example of functional redundancy. In a diverse community (left), the loss of one pollinator species is offset by other species; however, in a depleted community (right), the loss of one species leads to a drastic decrease in the pollination service.

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CHAPTER 2
STATUS AND TRENDS OF POLLINATOR COMMUNITIES AND POPULATIONS

2.1 GENERAL POLLINATOR DECLINES

There is extensive proof that the populations of many insect species are experiencing **declines in their population**. This proof increases quickly as longer time series of tracking or monitoring programmes are amassed. Different reviews conclude that insects are suffering an unprecedented, extremely concerning decline worldwide [1–4]. It has been estimated that the biomass from flying insects in nature conservation areas in Germany has decreased by around 70% in the past 25 years [5].

Insect pollinators are a clear example of this trend, and the decline of this group is now accepted as a widespread, global phenomenon [6–13]. These declines have been particularly studied in **butterflies** and **bees** and, to a lesser extend, in **syrphids** (Syrphidae). It is important to note that the declines do not affect all species equally. In the case of bees, for example, large-sized species, those with a long proboscis, and those with a high degree of specialisation in terms of habitat and diet are most affected [8,10,14]. This relationship between biological traits and declines leads to a **depletion of functional diversity** and to **biotic homogenisation** which could endanger the pollinating function throughout the community, as explained in Section 1.8.

In Catalonia, the only group of insect pollinators for which information on population trends is available are diurnal butterflies. Monitoring over the past three decades of a large number of population in Catalonia, Andorra and the Balearic Islands as part of the **CBMS** (**Catalan Butterfly Monitoring Scheme**; www.catalanbms.org) shows a 70% decline of the species [15–17] (Fig. 9), confirming the negative trends detected in Europe and worldwide. The conclusions reached from different types of analyses are extremely

REGRESSION OF THE BLACK-EYED BLUE

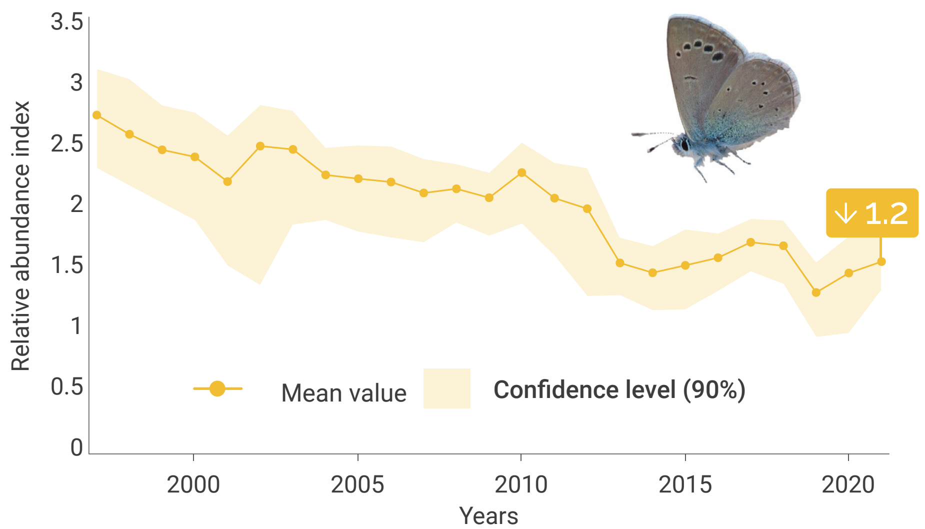


Fig. 9. Regression of the black-eyed blue (*Glaucopsyche melanops*; Lycaenidae) in Catalonia during the period 1998–2021 (Source: CBMS, https://www.catalanbms.org/; MCNG, http://www.mcng.cat/).

similar and illustrate very strong patterns. Similar to bees, butterflies behaving as habitat specialists are those to have undergone the most significant declines [18]. In Europe, declines are particularly significant in species associated to open spaces [19]. This trend is also observed in Catalonia, where butterflies associated to meadows and grasslands have declined much more than those preferring forest environments [20]. A recent analysis also shows that butterfly species that are trophic specialists during their larval phase recorded the most significant declines [17]. This result is foreseeable to a certain extent, as different ecological traits (such as the degree of specialisation and the mobility of larvae and adults) correlate with each other and form a gradient ranging from a generalist ecological strategy to a specialist one [21]. As is the case with bees, these trends lead to a homogenisation of communities, which is ultimately explained by the local extinction of certain species. Based on data from the CBMS, it is estimated that these local extinctions affect approximately 5% of the butterfly populations monitored in Catalonia [22].

2.2 THREATENED SPECIES

Unlike many groups of vertebrates and plants, knowledge of the distribution and trends of most pollinator populations is scarce, which restricts their inclusion on the lists of threatened species and, ultimately, their legal protection. Despite this, over recent years the IUCN has published several **Red Lists** of insect pollinators in Europe, partly based on the criteria of experts who help put this problem into context. For example, the red list of European bees estimates that 37% of the species on which there is sufficient information are in decline, and 9% are classified as threatened. The group of bumblebees is particularly noteworthy, with 26% of threatened species. This red list acknowledges that there is insufficient data on 57% of the species to be able to assess their conservation status [23]. In the case of diurnal butterflies, the European red list estimates that 31% of the species are in decline and 9% are threatened [24]. In terms of each country, the proportions of species in each category of threat largely reflects the level of knowledge of regional fauna. Hence, an analysis of the 34 red lists available shows that in southern countries, with richer yet much less well-known faunas, the average value of categories of threat is much lower than that of central and northern countries [25].

The Red List of Invertebrates of Spain [26] includes 35 pollinator species in different categories of conservation (Fig. 10). These include a species of flower-visiting coleoptera (classified as vulnerable), 3 species of syrphids (one endangered), 17 species of bee (four endangered) and 14 species of Lepidoptera (three endangered). The list also includes another 36 near threatened pollinator species, although with insufficient data.

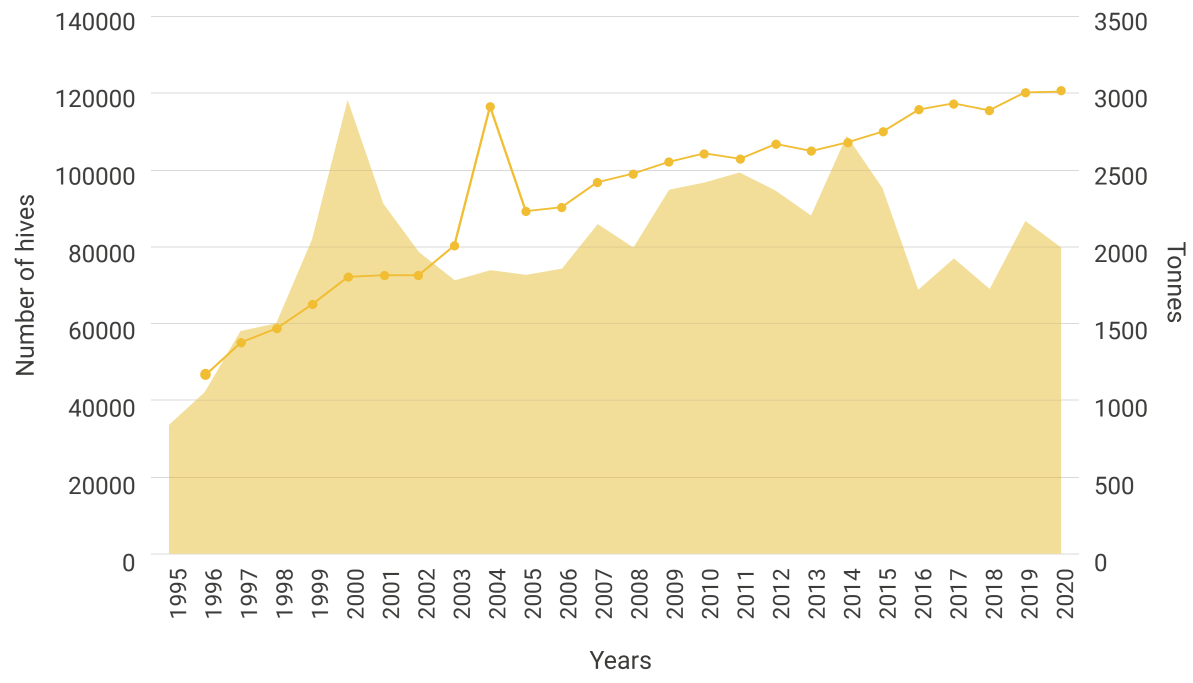
In Catalonia, the **Catàleg de la Fauna Salvatge Autòctona Amenaçada** (Catalogue of Threatened Native Wild Fauna) includes a list of animal species for which there is solid evidence of them being threatened. This Catalogue includes 45 species of diurnal butterflies (12 endangered, 32 vulnerable, and one extinct for reproduction in Catalonia). The list was compiled based on the proposed categories of threat included in the Guide to Diurnal Butterflies of Catalonia [27], established using relatively accurate data on distribution and trends. Thanks to this data, it can be confirmed that 20% of the diurnal butterfly species in Catalonia are threatened. In terms of the remaining pollinators, the scarcity of threatened species merely reflects a lack of knowledge of the distribution and status of the population, which hinders their objective classification. The Catalan catalogue includes no diptera, although it does contain three flower-visiting Coleoptera (one classified as endangered and the other two as vulnerable), and two species of bumblebee (both classified as vulnerable). In countries where there is information on the population trends of bees, such as Germany, 49% of the species are considered to be in decline [28]. A study performed in the United Kingdom indicates that 33% of the species of bees and syrphids have declined and 10% have increased since 1980 [29].

Fig. 10. The marsh fritillary (*Euphydryas aurinia*; Nymphalidae) is a species protected by the Habitats Directive of Catalonia. Despite this, the populations occupying the Mediterranean sector (which are most of them) are suffering an extremely significant regression due to the eradication of former fields and grasslands and to the progressive reduction and fragmentation of their habitat (Photo: J. Corbera).

2.3 HONEY BEE POPULATION TRENDS

A lot has been commonly said about the decline of the populations of honey bee, *Apis mellifera*. Although the number of hives has decreased significantly over recent decades in some countries, such as the United States and Germany, this is not a generalised trend [30]. Despite the growing difficulties faced by the beekeeping sector in the shape of new pests and diseases, hive depopulation syndrome and high levels of winter mortality, along with competition for the importing of honey from other countries [31], the number of hives in Spain has increased consistently since the '80s (Fig. 11; [32]). In Catalonia, the **number of hives** has risen from 46,500 in 1996 to 122,000 in 2020 (Fig. 11; [32]). Most of these hives (78%) are nomadic [32]. The majority of Catalan beekeeping operations (71%) deal in honey production, whereas as 23% combine honey production with crop pollination and 3% deal exclusively in pollination [32]. Over recent years in both Catalonia and Spain, the rise in the number of hives has not led to an increase in honey production (Fig. 11). The reasons for this apparent drop in honey production per hive are unclear, and undoubtedly involve many different factors. Periods of drought associated with the current situation of climate change have a significantly negative impact on blooms. This leads to a state of malnutrition which weakens bees, affecting the capacity of their immune system to deal with parasites such as the varroa and the viruses it transmits, along with other pathogens (fungi, bacteria and other viruses) [33–36]. All this results in the **weakening of colonies**, jeopardising their honey production capacity (Section 3.8.2).

01 EVOLUTION OF THE NUMBER OF HIVES AND HONEY PRODUCTION IN CATALONIA (1995–2020)



02 EVOLUTION OF THE NUMBER OF HIVES AND HONEY PRODUCTION IN SPAIN (1985–2020)

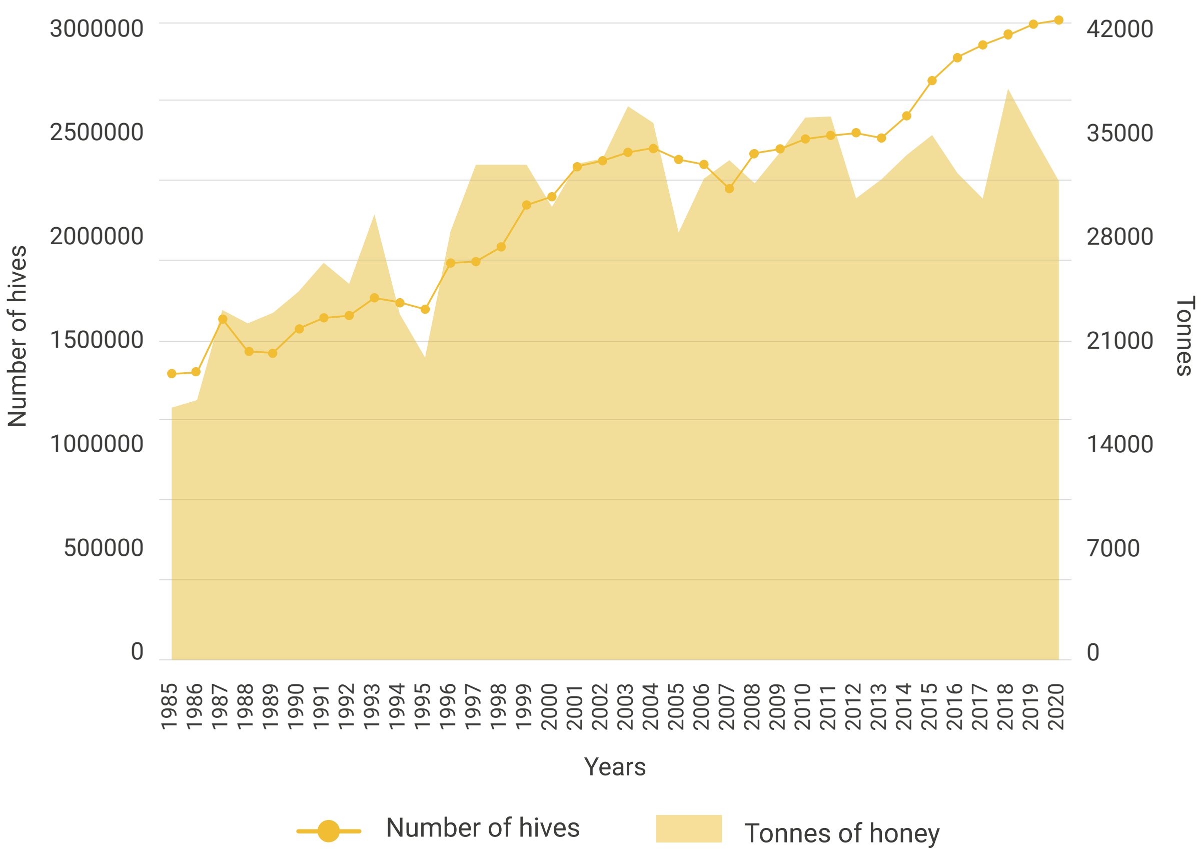


Fig. 11. Number of registered hives and honey production in Catalonia (01) and in Spain (02) over recent decades. (Source: [32])

2.4 MANAGED POLLINATORS

As of the early 20th century, **honey bee**, *Apis mellifera*, colonies were used not only to obtain honey, wax and other bee-related products but also to increase pollination in cropland. Since then, thanks to its availability in large quantities and its versatility, this species has been used as the principal —and in many cases the only— managed pollinator in most crops around the world.

Depending on one single species of pollinator for all crops is, however, risky. Firstly, problems in the supply of this pollinator could have serious consequences on agricultural production as a whole. Secondly, despite the honey bee being an eminently generalist species which visits almost any type of flower, its pollination effectiveness is not very high on some crops or it might prefer to visit other flowers, which means that other densities (hives per hectare) must be used to obtain good pollination levels. Breeding and management methods for other species of bees have therefore been developed for specific crops (Fig. 12). Since the 1960s, populations of a solitary leafcutting bee, *Megachile rotundata*, have been commercialised to produce alfalfa seeds [37]. More recently in Europe in the 1990s, colonies of bumblebees (*Bombus terrestris*) were used to pollinate tomatoes and other greenhouse crops [38]. The breeding of **bumblebees** rose very quickly, and they are now also used to pollinate fruit trees [39]. Their use in Catalonia is relatively widespread in both greenhouse crops (strawberries) and in orchards. Four species of **solitary bees** in the genus *Osmia* are being used in eastern Asia (*Osmia cornifrons*), North America (*Osmia lignaria*) and Europe (*Osmia cornuta* and *Osmia bicornis*) to pollinate fruit trees [40], although

Fig. 12. Three managed pollinator species visiting fruit tree blossom. (**01**) The honey bee (*Apis mellifera*; Apidae); (**02**) the buff-tailed bumblebee (*Bombus terrestris*; Apidae); (**03**) the European orchard bee (*Osmia cornuta*; Megachilidae). (Photographs: N. Vicens).

the commercialisation of these species has not grown to such an extent as that of bumblebees. In Catalonia, some associations of fruit growers are breeding small-scale populations of *Osmia cornuta*.

Managed pollinators have a clearly positive impact on the levels of pollination and productivity of many crops. Despite this, as explained in Section 3.9, their use may also involve certain risks to wild pollinators.

2.5 EXOTIC SPECIES

The introduction of **exotic** (or **foreign**) species, whether inadvertently or intentionally, involves a series of significant risks. Some of these species may become invasive and interfere with the functioning of the ecosystems, even having a negative effect on the production economy and the well-being of human populations [41].

The **intentional introduction** of pollinators is not frequent practice, although in the late 1970s a solitary Asian bee, *Osmia cornifrons*, was introduced into the United States to pollinate fruit trees [42]. Since then, this species has established natural populations in large areas of the country. More recently in 1997, the European bumblebee *Bombus terrestris* was introduced into Chile to encourage the pollination of greenhouse crops [43]. It has now spread throughout Chile and Argentina, with extremely negative consequences for some species of native bumblebees (Section 3.8.1).

The number of exotic species of animals and plants in Catalonia stands at 1235 [44]. These include some pollinators.

2.5.1 Bees

The giant resin bee, *Megachile sculpturalis* (Fig. 13), was detected for the first time in Europe near Marseilles (France) in 2008. The way in which it was introduced is unknown, although because this species makes its nest in pre-established cavities (in cane, for example), it is likely that some nests were introduced along with a cargo of goods. It has expanded very quickly and can now be found in 13 European countries. It was detected for the first time in Catalonia in 2018 [45,46]. This species has also been introduced into the United States where it has colonised most of the states in the east of the country.

2.5.2 Wasps

The Asian hornet, *Vespa velutina* (Fig. 13), is a social wasp originating from eastern Asia, which was detected for the first time in Europe (in south-western France) in 2004. It mostly likely arrived in France in the form of one or more fertilised queens in containers of pottery imported from China. Since then, it has expanded relatively quickly and has now been detected in 8 European countries [47]. It was detected for the first time in Catalonia in 2012 [48]. Since then, it has spread through most of the territory, with most impact on the province of Girona [49]. The Asian hornet builds large nests, with colonies of up to thousands of individuals [47]. It is a generalist predator for which honey bees make up a significant part of its diet [50], meaning that its expansion is a threat to beekeeping (Section 3.8.2). Like other social wasps, the Asian hornet actively defends its nest. It normally nests in tree branches of a certain height, where it poses no real danger to human populations. However, it sometimes makes its nests in slopes, hedgerows, buildings and other constructions in inhabited areas, creating a perceived lack of safety to public health. A

Fig. 13. Two species of exotic hymenoptera. (**01**) The giant resin bee (*Megachile sculpturalis*; Megachilidae) visiting flowers of the chasteberry, *Vitex agnus-castus*; (**02**) the Asian hornet (*Vespa velutina*; Vespidae), visiting flowers of the rosemary, *Rosmarinus officinalis* (Photographs: N. Vicens).

nest of another exotic wasp, *Vespa orientalis*, was recently detected at the port of Barcelona [51]. This nest was eliminated, and it is currently unknown whether this was an isolated case or whether there are other nests in the area. Nests of this species, which is also a predator of the honey bee, have been detected over recent years in Andalusia and Valencia [52]. Another exotic wasp also of Asian origins, *Vespa bicolor*, has been found in Andalusia [53]. These three exotic species are related to the European hornet, *Vespa crabro*, a native species which poses no threat to honey bees and which is protected in some Central European countries. Other exotic wasps present in Catalonia, all of which are solitary, include *Isodontia mexicana*, *Sceliphron curvatum* and *Trypoxylon petiolatum* [53–55]

2.5.3 Butterflies

The only exotic diurnal butterfly in our fauna is the geranium bronze, *Cacyreus marshalli*, a species originating from South Africa which was inadvertently Introduced into Catalonia in 1989 through the import of horticultural geraniums (genus *Pelargonium*) [56]. There was an unusual abundance in the early '90s, possibly due to the lack of natural enemies. Its numbers have subsequently curbed, most likely as certain parasitoids have been included in its diet. Even so, this species has become a regular and even abundant inhabitant in Catalan villages and cities, making the most of the custom of using geraniums as ornamental plants. Another non-native diurnal butterfly that occasionally appears in Catalonia is the monarch butterfly, *Danaus plexippus*. Although the initial sightings, which date back to 2003 and 2004 in the Ebro River Delta, can be attributed to the rather exceptional arrival of migratory specimens from the south of Spain (where there had been stable populations for over a century), there were new sightings in coastal areas (including the city of Barcelona) as of 2011. Sightings have been rarer inland, corresponding almost certainly to reared specimens released during wedding and birthday celebration. This practice, which has become commonplace over the past decade in different points of Spain, has also been recorded in Catalonia [57]. Although some released females have been able to successfully reproduce thanks to the presence of caterpillar foodplants (naturalised Asclepiadoideae), the populations of this subtropical butterfly die out with the arrival of winter.

Also worth noting is the detection over recent years of some specimens of butterflies under the genus *Morpho*, originally from Mexico, Central America and northern South America, in different areas of Catalonia, especially the city of Barcelona. These butterflies have most likely escaped from butterfly farms or private (parties) or public (art exhibitions) events.

The problem of invasive species is much more serious in the case of certain nocturnal butterflies, including the box tree month, *Cydalima perspectalis*, detected for the first time in La Garrotxa in 2014, soon after which it became a serious pest for box trees in different Catalan districts [58]. This species is native to the subtropical regions of eastern Asia (Korea, China and Japan). It was detected for the first time in Europe in south-western Germany in 2007, where it was introduced inadvertently, most likely through the sale of ornamental plants of the genus *Buxus* [59].

2.6 EVIDENCE OF CHANGES IN PLANT-POLLINATOR INTERACTIONS

In addition to changes in population trends and in the composition of pollinator communities, changes have also arisen over the past century in the relationships that pollinators establish with plants. In a study conducted in the Netherlands, the pollen collected by wild bees was analysed in museum specimens before and after 1950 [60]. The analysis showed that many species of bee have substantially changed their diet, and that these changes were particularly notable in the species that have declined the most.

The study also provided evidence that the changes in the abundance and distribution of plants has led to a change in diet towards less suitable plants. The current situation of climate change affects the phenology of both plants and pollinators. As explained in Section 3.7.2, a different response to climate conditions by these two groups of organisms can create time-based imbalances, forcing pollinators to collect pollen and nectar from less preferential plants.

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CHAPTER 3
CAUSES OF POLLINATOR DECLINE

There are many causes resulting in pollinator declines, although they generally coincide in the different geographical areas studied and are related more directly to the phenomenon of global change, which includes the recent change in land and landscape uses and climate change.

3.1 AGRICULTURAL INTENSIFICATION

One of the maximum exponents of the change of land uses and the transformation of the landscape was the drastic change in agriculture following the Green Revolution of the 50s and 60s, with a new paradigm based on **agricultural industrialisation** and increased production due to the application of new practices and technologies. These changes led to what is known as **agricultural intensification**, characterised by a more intensive use of the land and a series of practices such as the use of heavy machinery, an increase in the size of cropland plots, the trend towards **monoculture**, and the use of chemical **fertilisers and pesticides** [1]. This process brings with it the destruction of the margins of fields and the **disappearance of semi-natural habitats** and fallow land, thus decreasing the abundance and continuity of floral resources and altering nesting substrates. It also involves an increase in the environmental load of toxic products. Agricultural intensification has generally led to a significant increase in the **landscape homogenisation**, reducing the mosaic configuration and the connectivity between habitats, with extremely negative consequences for biodiversity in general[2]. Another factor associated directly with agricultural intensification is irrigation, which allows for a drastic increase in agricultural production yet significantly changes the landscape and the plant life that coexists with the crops. A recent article [3] provides a summary of the problems of agricultural intensification in relation to inset decline, which is particularly significant in the case of pollinators [4,5]. Most agricultural production worldwide is concentrated in areas of intensive agriculture. Pollinator species are also most threatened in these areas, which is a problem for their conservation and for maintaining the ecosystem service they provide [6,7].

In terms of landscape, agricultural intensification is characterised by the loss of semi-natural habitats and a reduction in crop diversity. Locally, it is characterised by an increased use of fertilisers and plant protection products, a simplification of rotation systems, a decrease in crop diversity, and an increase in the frequency and depth of land disturbance [8]. These practices have a significant impact on weeds (herbaceous species of cropland), causing drastic changes in the coverage and diversity of floral communities and leading to a significant decrease

HISTORIC DISTRIBUTION OF *ZEGRIS EUPHEME* IN CATALONIA

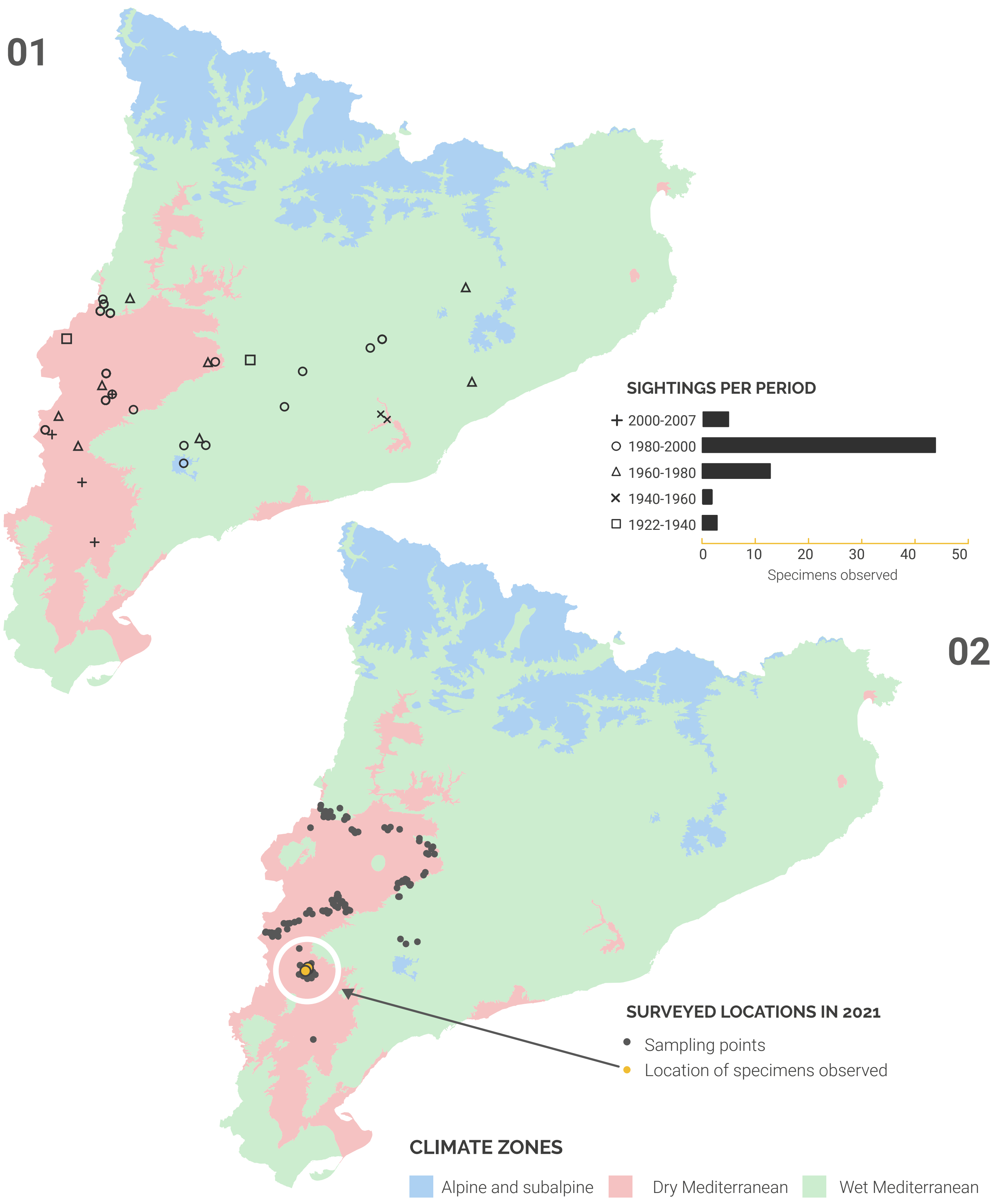

Fig. 14. Distribution of *Zegris eupheme* (Pieridae) in Catalonia. (**01**) Location of sightings between 1922 and 2007. (**02**) Surveyed locations in 2021; the yellow dots indicate the only location where the species was found (Source: [24])

in the availability of nectar and pollen in agricultural environments [9–12].

This **floral transformation** has great repercussions on pollinators. Both the taxonomic diversity and functional diversity of pollinator communities decrease with agricultural intensification [6,13–16]. This decrease does not affect all species equally. For example, larger bees may find it easier to disperse and to find resources than smaller bees [17,18], although in turn they may be more exposed to pesticides by travelling longer distances [19]. Pollinators find it harder to find food in conditions where flowers are scarce. A recent study shows that some bees have a small body size in agricultural (and urban) environments than in natural environments [20]. Bees react to the scarcity of flowers by producing smaller individuals or by predisposing the proportion of sexes towards males, which have a smaller body size and require less food [21,22]. This response has consequences in terms of winter mortality (small individuals are more likely to die in winter) and leads to an imbalance in the proportion of sexes in the population.

In Catalonia, different studies confirm a loss of abundance and of richness of butterfly communities in agricultural areas, while identifying certain species that could be used as indicators of the impact of intensification [23]. For example, a systematic review of dryland in Lleida in 2021 indicated that the sooty orange tip (*Zegris eupheme*), a specialist butterfly in this type of habitat, has undergone a drastic decline over the past fifty years, making it one of the most threatened invertebrates in Catalonia [24] (Fig. 14). The collapse of this butterfly's populations is undoubtedly related with the intensification of its habitat, and even the transformation of some of the drylands in irrigated orchards and the progressive disappearance of fallow land.

Another study, also conducted in the region of Lleida, indicates major changes in the floral composition of plant life associated with almond fields due to irrigation, with significant repercussions on the composition of bee communities. Bee communities are less abundant in dryland areas, although they tend to be less diversified. Furthermore, the functional composition of these communities is radically different. Solitary species prevail in dryland areas, and social species in irrigated areas [25].

Another factor closely linked to agricultural intensification and pollinator declines is the use of plant protection products. Given its importance and complexity, this matter is discussed in a separate chapter (Chapter 4).

3.2 GENETICALLY MODIFIED (GM) CROPS

Genetically **modified crops** are plant varieties in which the genome has been modified using genetic engineering techniques in order to give the plant new properties that can improve its agronomic behaviour, including its resistance of pests, disease, herbicides and aspects related with the nutrient profile and maturity, among others. In terms of the possible repercussions for pollinators, GM crops can be divided into three types: (1) Those modified for resistance to broad-spectrum herbicides, to allow for treatment with these products without affecting the crop; (2) those modified for the production of different toxins that have an insecticide effect, primarily on Lepidoptera and Coleoptera larvae; (3) those modified by introducing double-stranded RNA which are taken up by the insects feeding on the plant and which only act on the target species (the pest to be controlled), causing its death [26]. The latter is a recent method which is currently being used on corn in some countries, such as the USA and China [27,28]. Experiments are also underway with the spraying of this type of genetic material directly onto the plant.

The only GM crop permitted in some European Union countries, including Spain, is **corn**, which expresses the Cry1Ab toxin and provides resistance to two significant pests, the borers *Ostrinia nubilalis* and

Sesamia nonagrioides. In 2018, this crop covered an area of 121,000 hectares in the European Union, mostly (96%) in Spain where it accounted for 35% of the total area of corn [29]. After Aragon, Catalonia is the autonomous region with the greatest extension (27,152 ha) of GM corn (over 50% of the total area of this crop; [30]). One possible risk associated with GM crops that synthesise Cry proteins arises from the fact that their pollen also has insecticide properties. This means that, when it is dispersed by the wind and deposited on foodplants of different Lepidoptera or Coleoptera to the pest species, there is a risk of it being passively ingested which would lead to their death. This possibilities was extensively discussed following an initial study alerting to the risk to populations of the monarch butterfly, *Danaus plexippus*, in the United States [31]. It was ultimately concluded, however, that the decline of this butterfly could not be related with this ingestion but instead with the disappearance of its foodplants. Similarly, a study performed in Catalonia using climate data from the Baix Empordà region and data on the *Aglais io* butterfly population concluded that mortality from the passive ingestion of pollen grains from GM plants deposited on its foodplants is negligible at distances of over 10 m from croplands [32]. During a scarcity of flowers, in the summertime for example, honey bees can collect and consume pollen directly from corn [33]. Despite this, most studies on bees and butterflies have detected insignificant effects on the survival of both adults and larvae [29,34–36].

Herbicide-resistant **GM crops** promote the use of these products to control plants that could compete with the crop. They might therefore have an indirect, negative effect on pollinators because they suppress flower-producing plants and/or those used as food for butterfly larvae and other pollinators. As indicated, the major decline of the monarch butterfly in North America is related with the disappearance of its foodplants (different species under the genus *Asclepias*) in fields of GM corn treated with herbicide [37,38]. Based on this evidence and following the recommendations of different studies [39], European legislation does not allow for herbicide-resistant GM plants to be introduced until any direct effects on pollinators and the possible environmental effects arising from the increased use of herbicides associated with these crops have been evaluated [29]. Even so, European legislation does allow for the use of varieties which, despite not being GM, are resistant to herbicides. These include some sunflower varieties obtained either through hybridisation with natural wild populations which express diverse resistance genes or through site-directed mutagenesis processes.

3.3 URBAN DEVELOPMENT

Another process in the change of land uses which has radically transformed the landscape over the past century has been the huge strides in **infrastructure and urban development**. This affects extensive areas of territory, with a clearly negative impact on plant life and nesting habitats and, therefore, on pollinators [40]. Likewise, however, urban centres with appropriately managed green spaces are also able to provide certain characteristics favourable to pollinators, such as a great diversity of flowers for a regular supply of floral resources (despite these often being pre-eminently exotic species), a limited use of pesticides, and the availability of artificial nesting substrates for cavity-nesting species.

Different studies have compared pollinator communities in urban environments with agricultural and/or natural environments, with opposing results. Some of these studies have found that the richness and/or abundance of bees and butterflies was greater in urban environments [41–44]. Some studies, however, found a negative relationship between the abundance and richness of pollinators and the degree of urban development [45–49]. The response by pollinators to urban development depends on their biological traits, among other factors. Bumblebees, solitary cavity-nesting bees, and small species are, in principle, the most commonplace in urban environments. Floral specialists, however, are rare. Syrphids generally have a more negative response than bees to urban development [50–52].

The effect of urban development on pollinators depends largely on the density of **green spaces** and on their management (Section 9.3). Along these lines, it is worth noting that most studies on the matter have been made in countries in northern and central Europe and in the United States, with a different urban development model to that of most Mediterranean countries. Urban development in Catalonia has had an unequal effect on the territory. CBMS data on the time-based dynamics of the distribution of some butterfly species show very strong declines and even the local extinction of butterfly populations that formerly occupied areas in the suburbs of Barcelona, Vallès Occidental and Baix Llobregat, among others.

3.4 POLLUTION

In addition to pesticides, pollinators may be exposed to different toxic substances from **industrial activity** and urban development, such as heavy metals and other contaminants such as selenium, arsenic and nitrogen. **Heavy metals** (lead, cadmium and zinc, among others) can come into contact with pollinators via air, water or sun, and also via flowers [53]. Little investigation has been made into their effects, although some studies have found a negative relationship between the abundance, diversity and reproductive success of solitary bees and pollution levels [54,55]. Other studies suggestion that pollution from heavy metals is related to declines of the *Parnassius apollo* butterfly in Finland [56]. **Contaminants** can also indirectly affect pollinators through their effect on plant life. A study conducted in California shows that the deposition of nitrogen near motorways favours the growth of gramineae, reducing the abundance of caterpillar foodplants and leading to the decline of butterfly populations [57]. More recently, experiments have shown [58] that high nitrogen concentrations in foodplants (simulating those occupying environments subject to intensive agriculture) have a negative effect on four diurnal and two nocturnal butterfly species, reducing larva survival by one third. The authors concluded that, in many agricultural environments, over-fertilisation exceeds the physiological tolerance of many butterflies.

3.5 AFFORESTATION

Insects pollinators depend on flowers for their food, exclusively so in the case of bees. Communities of bees and other pollinators are therefore richer and more abundant in open environments than in dense forest areas in which the undergrowth receives little light and there are few flowering plants. In open areas, furthermore, direct sunlight provides more efficient thermoregulation, which is necessary in ensuring most pollinators are able to remain active. Therefore, clearings in forest areas are an important element of the landscape for maintaining the diversity of pollinators. One study performed in La Garrotxa shows that communities of cavity-nesting bees are richer and more abundant in clearings (basically, previous extensive farming operations) than in adjacent forest areas [59]. Wasp communities, however, which are less dependent on flowers, are similar in both types of environments.

The abandoning of traditional agricultural-livestock practices and the consequent **eradication of habitats** are, as a whole, one of the main factors in pollinator decline. This phenomenon is widespread in the Mediterranean basin [60,61] and, more specifically, in Catalonia [62]. This problem was analysed in the case of diurnal butterflies [63]. Up to 91% of all diurnal butterfly species in Catalonia prefer open environments to closed, and their habitat is formed by different types of meadows and pastures. An analysis of the changes in plant life in over fifty locations monitored for more than two decades shows an eradication of plant life due to the abandonment of traditional farming practice. These two facts together explain part of the generalised decline observed in populations of many species of butterflies.

3.6 HABITAT FRAGMENTATION

The combination of some of the factors discussed in the previous sections (agricultural intensification, urban development, afforestation) has led to the fragmentation of favourable habitats for pollinators [64]. This leads not only to the decline but also to the break in continuity of these habitats, which become a group of disconnected spots. As a result of this process, the distance between favourable habitats has increased due to the creation of **barriers** which insect pollinators find difficult to cross, such as extensive urban areas or those occupied by dense forests [65]. These changes in the structure of the landscape restrict the movements and the survival of pollinators [66]. Different studies show that fragmentation reduces the abundance and diversity of pollinators, with consequences on the pollination levels and reproductive success of entomophilous plants [65,67–69]. Fragmentation has diverse effects on pollinators which depend on the spatial scale, the habitat and the group of pollinators studied [70]. On a small scale, fragmentation can reduce the **connectivity between nesting habitats** and food resource habitats. On a larger scale, it can reduce the gene flow between populations. Both in bees and in butterflies, sedentary species (with little dispersion capacity) with a more specialised diet are most affected by fragmentation [71,72]. The fragmentation of habitats has especially affected species that are structured into metapopulations, which are those formed by a group of local populations in which their individuals interact [71].

3.7 CLIMATE CHANGE

The current process of climate change became apparent as of the second half of the 20th century and involves a progressive change in climate factors such as **temperature** and **rainfall**, attributed to the increase in CO_2 levels as a result of the use of fossil fuels. The main consequences of climate change in the Mediterranean basin are the generalised increase in temperature, the drop in rainfall, and the increased frequency of episodes of extreme conditions, such as long periods of drought or intense rain [73]. Climate change can affect pollinators both directly and indirectly through its effects on flowers and on the food resources of larvae. These effects ultimately affect not only the abundance and diversity of pollinators but also their geographical distribution, phenology, and interactions with plants [74–77].

The effects of climate change are partly determined by the biological traits of species and by the location of populations within the geographical range of the species. Along these lines, it must be noted that the Mediterranean region is the southern distribution limit for a significant number of insect pollinators. This means that, in light of an increase in temperatures, Mediterranean populations can be rapidly excluded from the thermal niche to which these species have adapted. The reverse occurs at higher latitudes. In these cases, global warming may be a new opportunity to occupy areas that were out of their range because they were too cold.

3.7.1 Effects on the biological life cycle

The generalised rise in temperatures has a direct effect on the **development rate** of insects and on their survival [78]. In the case of bees, available evidence indicates that these effects may have significant consequences on the populations. It has been observed in southern England that, during years with mild autumns, some queen bumblebees, *Bombus terrestris*, do not enter diapause and start forming colonies in the autumn instead of waiting for spring [79]. Parallel studies have shown that the workers of this species are less resistant to the cold than the queens and, therefore, colonies started prematurely could disappear in the event of long periods of negative temperatures during wintertime [80]. Solitary bees of the genus *Osmia* reach adult stage in the autumn, just before the arrival of winter temperatures, and they spend the winter in this stage without leaving the cocoon. In years when winter arrives later, adults are exposed to mild temperatures which leads them to consume fat reserves, resulting in significant weight loss which could increase winter mortality [81,82].

The relationship between significant annual fluctuations in the populations of many butterflies and the weather is being investigated in Catalonia. Data indicates that both warm winters and dry springs have an extremely negative impact on the abundance of butterflies, quite possibly through considerable increases in larva mortality [83]. In the case of the former, high temperatures lead to a decrease in the reserves that larvae of many species need to get through the winter, resulting in lower survival rates during this period. In the case of the latter, the lack of rain results in a decline in plants at a time of maximum development of the larvae of many species, which also results in lower larval survival rates. Climate model projections in the Mediterranean area indicate that both climate abnormalities, dry springs and warmer winters, will be increasingly frequent in the future. This means that climate change may have extremely negative repercussions on butterfly populations.

3.7.2 Phenological changes

Some studies show that pollinators bring forwards their period of activity in response to climate change [84–89]. These **phenological changes** can lead to time-based imbalances between the pollinator and the plants it visits. For example, the response to climate change may vary in size between the pollinator and the plant, with one bringing its cycle forwards more than the other. The phenology of the pollinator and the plant may also be regulated by different stimuli, such as the temperature (which rises with climate change) and the photoperiod (daytime hours of sunlight; which is not affected by climate change). Different studies have found that the phenological response to climate change varies between flowers and pollinators, although not always in the same way. In some cases, the phenology of pollinators advances more than that of flowers, and in other cases the opposite occurs [86,90–93]. These imbalances may be particularly significant in the case of specialist pollinators, which depend on a small number of plant species. Drought conditions might also cause imbalances between the flight period of butterflies and the peak bloom dates of their preferred flowers, as could be seen from long-term data from a locality in Els Aiguamolls de l'Empordà [94]. Evidence has recently been found that the butterflies in most decline in Catalonia are those with least phenological plasticity, which could be due to a loss of synchrony with the plants on which they depend [95]. In short, these imbalances may alter the interaction network between plants and pollinators, with consequences that are difficult to predict for the reproductive success of pollinators and of plants.

3.7.3 Changes in geographical distribution

The effects of climate change on the **geographical distribution** of pollinators has particularly been studied in butterflies [96–98] and bumblebees [77,99,100]. Latitudinal and altitudinal movements of the populations of these species towards historically colder areas is being seen. In the case of the bumblebees of Europe and the United States, the northern distribution limits have not changed over the past century yet the southern limits have [100]. Furthermore, it has been seen that the species most affected by these changes are those with southernmost distribution.

As indicated, the Mediterranean region is the southern distribution limit for many pollinator species, making them particularly vulnerable to climate change. This situation is clearly seen in the relationships that have been established between the richness of butterfly species in Catalonia and different climate variables [101]. The richness of species follows a unimodal curve with the temperature, with a maximum number of species in colder areas which correspond to subalpine environments of the Pyrenees (Fig. 15). The richness decreases extremely quickly as we move towards warmer zones, which is also the case when moving towards colder zones of the high mountains. It is therefore foreseeable that climate warming will lead to a loss of species alongside a decrease in the area occupied by subalpine environments.

BUTTERFLY RICHNESS

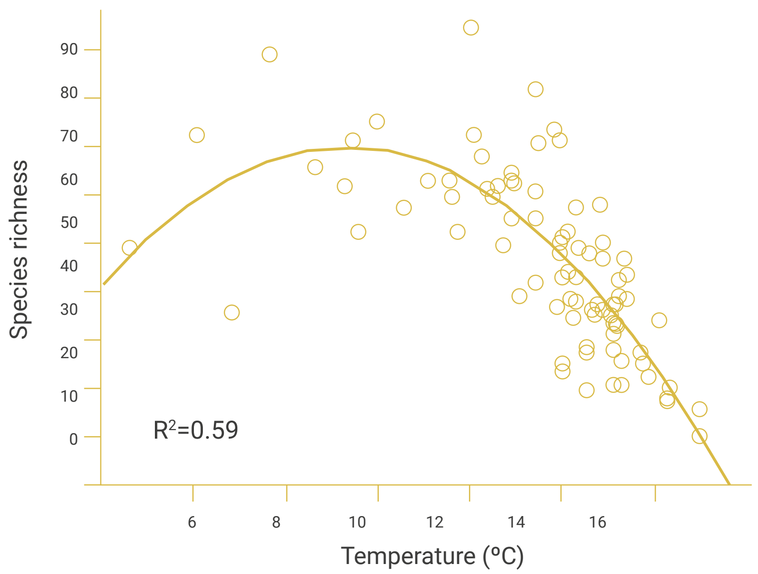

Fig. 15. Butterfly richness follows an extremely strong humped-back model in terms of temperature. Maximum richness is found in upland and subalpine belt environments. As the annual temperature rises (in progressively more Mediterranean environments, for example), butterfly communities rapidly deplete (Source: [101]).

3.7.4 Changes in floral resources

Climate change can directly affect pollinators through its effects on the availability of floral resources. Some studies show that plant exposure to climate change could degrees both their **bloom intensity** and **nectar yield** [102–104]. Once again, there is great variability among species. In Mediterranean plants, the rise in temperature reduces nectar yield in summer-flowering species but not in those flowering in spring [105]. The perception that climate change has a negative effect on honey production is widespread among beekeepers [106–108], and some studies have found that winter mortality in colonies of the honey bee increases with high summer temperatures [109,110]. In this case, however, the scarcity of floral resources might also involve other factors, such as attacks by mites *Varroa destructor.* In years with higher springtime temperatures, the hives produce more offspring, thus encouraging the spread of mites [111].

Climate change can also affect other traits of plants which play a significant role in their attractiveness to pollinators, such as floral scents [112]. As with phenological imbalances, these changes can affect interactions between the plant and pollinator communities and, ultimately lead to changes in their reproductive success.

3.8 BIOLOGICAL INVASIONS

The introduction of **exotic** (or **foreign**) plants and animals, which could become invasive, is increasing at an alarming rate worldwide and represents a serious threat to biodiversity in general and to pollinators in particular [113]. Some of these species have been introduced inadvertently although in other cases it has been intentional and authorised, with the species being considered to possibly have beneficial effects on socioeconomic or environmental activities. The introduction of exotic natural enemies for the control of pests (also normally exotic) started in the late 19th century and was an extensively used biological control strategy throughout the 20th century [114]. The possible impact of these introductions on native species and the consequent implementation of risk assessment and regulation methods have meant that this method of control has decreased quite considerably over recent decades [115,116]. There are recent cases of introductions, however, such as that of the parasitoid *Torymus sinensis* to control the chestnut gall wasp (*Dryocosmus kuriphilus*) in Spain and in other European countries [117]. Within the current context of the globalised movement of people and goods, however, most exotic species are introduced inadvertently through imports [118]. In this case, improved regulations on these imports are essential in reducing the impact of this channel of introduction (Section 8.5).

3.8.1 Exotic pollinators

In the case of pollinators, **invasive species** can even compete for food or nesting resources with native species. Some studies on the recently introduced Asian bee, *Megachile sculpturalis,* indicate that this species sometimes destroys the nests of native, cavity-nesting bees [119].

Furthermore, invasive species can be vectors of **exotic parasites or pathogens**, which could infect native species. This transmission could have a major impact on the populations of native pollinators which have not co-evolved with exotic parasites or pathogens and, therefore, have developed no defence mechanisms. Particularly of concern are intentional introductions with the approval of the governments. Experience shows that the health controls to which the introduced populations are subjected are often insufficient to stop the unwanted introduction of parasites and/or pathogens. As explained in Section 2.5, the European bumblebee *Bombus terrestris* was introduced into Chile in 1997 to pollinate greenhouse crops. Since then, the species has spread through Chile and Argentina and has become the most abundant bumblebee species in the wild in many areas [120]. Alongside the advance of *Bombus terrestris*, there has been a rapid decline in the native species *Bombus dahlbomii.* Different studies indicate that this decline was favoured by both the competition for floral resources [120,121] and the transfer of pathogens (the protozoan *Apicystis bombi*) from the European species to the South American species [122,123].

3.8.2 Natural enemies of the honey bee

The honey bee is, without a doubt, the pollinator species to have received the most negative impact from **exotic predators, parasites and pathogens**. In some cases, their condition as a managed species and the commercial activity related with beekeeping have favoured the introduction and expansion of these new enemies.

The Asian hornet, *Vespa velutina,* is a great predator of honey bees and other insects [124], which arrived in Catalonia in 2012. The impact of the Asian hornet on the honey bee is not only due to predation but also to the stress it causes on worker bees, which do not dare leave the hive when they detect the presence of the hornet [125]. Surprisingly, there is little information on the incidence levels (number of hives attacked) and on the financial impact of this predator. Data from the National Union of French Beekeepers indicates that 30% of hives in the department of Gironde were attacked in 2010 [125]. A study performed in France shows that attacks by the *Vespa velutina* lead to significant population losses, particularly in weaker hives [126]. The study also shows that, when the predator is extremely abundant and workers fail to leave the hive for collection purposes, the consumption of honey reserves rises, thus increasing the risk of the colony collapsing during the winter.

Varroa destructor is an Asian mite which parasitises honey bee hives. The original host of this mite is the Asian honey bee, *Apis cerana*, although it started to infest the European honey bee, *Apis mellifera*, in the mid 20th century. *Varroa destructor* spread throughout the world with the commercial movement of colonies and beekeeping material. It arrived in eastern Europe in the 1960s and in western Europe in the '80s. Its presence was detected in Catalonia in 1985. This mite feeds primarily from the fatty body of bee larvae, chrysalis and adults, and transmits different viruses, such as the deformed wing virus, which play a role in weakening and causing the death of the colony [127]. The global expansion of the *Varroa destructor* had a devastating impact on the wild colonies of the *Apis mellifera* [128]. This mite has drastically affected beekeeping practices and remains one of the main problems in beekeeping around the world [129]. The appearance of cases of resistance by mites to the acaricides normally used to combat them makes the control of this parasite particularly difficulty [130].

Nosema ceranae, is a microsporidian fungal pathogen which affects the honey bee. Like the *Varroa destructor* mite, it comes from the Asian honey bee, *Apis cerana*, and has recently infested *Apis mellifera* colonies. It was detected for the first time in the Iberian Peninsula in 2004 [131]. Although its effects are less serious than those of the *Varroa destructor*, some studies have related *Nosema ceranae* infections with hive depopulation syndrome [132].

Aethina tumida is a small beetle of African origin which attacks *Apis mellifera* colonies. It arrived in the United States in 1998, and has since spread throughout North America. A source was detected in Portugal in 2004, where it was introduced in queen rearing boxes originally from the United States. This source was eradicated. It was detected in Italy in 2014, its presence being confirmed in Calabria and Sicily where the movement of colonies was restricted in order to stop its expansion [133].

3.8.3 Exotic plants

The introduction of **plants in general** and, more specifically, of entomophilous species is a widespread phenomenon [113]. Many of this type of introduction are often inadvertent, although others are intentional and are associated to gardening or agriculture. These exotic species often colonise the environment and spread throughout the territory. Some of the plants visited by pollinators which have colonised natural and semi-natural environments in Catalonia are the ice plant (*Carpobrotus* spp.), the summer lilac (*Buddleja davidii*), the prickly pear cactus (*Opuntia* spp.), the Bermuda buttercup (*Oxalis pes-caprae*), the cruel vine (*Araujia sericifera*), the California poppy (*Eschscholzia californica*), the Japanese honeysuckle (*Lonicera japonica*) and the black locust (*Robinia pseudoacacia*).

The arrival of a new species that produces pollen and nectar could primarily be considered beneficial to pollinators. In fact, the introduction of exotic flowers could have extremely negative consequences. Given the generalist nature of many pollinators, the new flower species are rapidly visited by native pollinators [134,135], leading to changes in their collection decisions and imbalances in the interaction network structure [136,137]. Exotic plants often become dominant and produce large amounts of pollen and nectar in comparison with native plants. This leads to facilitation in some cases, where native plants benefit from the service of pollinators, attracted by the exotic plant [138,139]. In other cases, however, the introduced species competes with the native species for the pollinators [139,140]. These changes can even change the pollination levels and reproductive success of some plants [141,142]. Regardless of their effects on pollinators, exotic plant species can become invasive and ultimately displace native plant species.

Fig. 16. The bumblebee, *Bombus terrestris* (Apidae), visiting the flower of an ice plant, *Carpobrotus* sp., a species from South Africa which has been intentionally introduced as an ornamental plant. (Photograph: N. Vicens).

3.9 MANAGED POLLINATORS

The introduction of populations of **managed native pollinators** in crop fields is widespread practice and helps mitigate pollination deficits and ensure food stability. Despite this, the use of populations of managed pollinators could lead to certain risks for wild pollinators.

Firstly, the introduction of large populations could result in the **over-exploitation of floral resources**, not only of the crop but also of the flora growing beside it which is, in itself, relatively scarce in agricultural environments. Secondly, managed pollinators could be a source of **pathogens and parasites** which can infect local populations of wild pollinators. Different studies have recorded the transmission of pathogens from the honey bee to wild bees, although the effects of this transmission on populations of the latter is unclear [143–146]. Lastly, the introduction of managed populations of a pollinator in cropland areas could also lead to mating between managed and wild individuals and, therefore, alter the **genetic composition** of natural populations. In the 1990s, Spain saw the importing of a great many colonies of the north European subspecies *B. terrestris terrestris* of the bumblebee (*Bombus terrestris*), different to the subspecies present in the Iberian Peninsula (*B. terrestris lusitanicus*). Genetic studies show that the genotype of the commercial populations has spread throughout the Peninsula. Most of the natural populations show signs of hybridisation, particularly in areas near greenhouse crops [147,148]. The resulting genetic introgression of these hybridisations could alter the local adaptation processes of the native populations. The phenomenon of genetic introgression is also very clear in the honey bee. The typical subspecies in the Iberian Peninsula is *A. mellifera iberiensis*, and most managed colonies in Spain and in Catalonia correspond to this subspecies [149]. Despite this, the international trade of queens is fostering hybridisation with subspecies from other parts of Europe (particularly the *ligustica* subspecies from Italy) and with selected varieties, such as the Buckfast. This hybridisation could destroy the genetic composition of the native subspecies with the consequent loss of behavioural and physiological traits configured over long periods of local adaptation [150].

3.10 BEEKEEPING INTENSIFICATION

The honey has the unique capacity among European insect pollinators of directing individuals from the colony itself to a certain source of food. This quality enables it to effectively exploit the areas that are richest in floral resources. Therefore, as each colony contains hundreds of thousands of individuals, the installation of large apiaries in natural areas could lead to an **over-exploitation of floral resources**, creating situations of unfavourable competition for wild pollinators. According to calculations based on the quantity of pollen and nectar collected per hive, a medium sized apiary (40 hives) consumes the equivalent of four million wild bees in three months [151]. Furthermore, data from 30 countries in the Mediterranean basin indicate that the ratio of the abundance of wild bees to the abundance of honey bees (based on observed visits to wild and cultivated flowers) has dropped from 4:1 in the 1960s to 1:1 in the 2010s [152].

Considering that the collection areas of a colony can be of a radius of over 1.5 km around the hive [153], proving that floral resources have reached their limit is not an easy task. Different studies and reviews on this matter conclude that signs of competition cannot be generalised but are relatively frequent [143,154–157]. A typical example can be seen at El Teide (Tenerife) National Park, where around 2700 hives settle each spring. This drastic increase in population leads to a depletion in the diversity of wild pollinators and changes in their interactions with plants [158]. In a study conducted at El Garraf Nature Reserve, it was detected that the consumption rates of pollen and nectar increased near the apiaries where there was a greater density of honey bees, and the presence of large, wild bees decreased [159]. Another study performed in the south of France found that, in conditions of significant hive density, visits by wild bees dropped by 55% [160]. This study also detected that, in situations of significant hive density, the amount of nectar and pollen collected per hive dropped by 44% and 36%, respectively, indicating a situation of intraspecific competition between the honey bee colonies themselves. Ideally, a hive **carrying capacity** should be established for each area to guarantee adequate levels of floral resources to maintain the communities of wild pollinators and to ensure the yield of the hives. Setting these thresholds is a complex task, partly due to said extensive flight radius of the honey bee and partly due to the significant annual fluctuations in flower production [161].

In Catalonia, the location of beekeeping sites must respect certain minimum distances between operations and in relation to areas of population, rural housing, livestock facilities and local roads or paths in order to avoid the risk of people or livestock being bitten. According to current law, beekeeping is considered a harmless activity and even environment friendly. In Catalonia, there is a programme of grants for hive installation in order to improve biodiversity in fragile agroecosystems where there may be relict species through activities aimed at promoting beekeeping systems which include a more extensive area [162].

3.11 INTERACTIONS BETWEEN FACTORS

It is important not to lose sight of the fact that the different stress factors to which pollinators are subjected act jointly, and may interact not only cumulatively but also **synergistically** [163,164]. This makes it difficult to attribute a specific impact to each factor affecting pollinator decline.

Many of the factors discussed until this point, such as agricultural intensification, the destruction and fragmentation of natural habitats, climate change, and beekeeping intensification contribute towards a reduced availability of floral resources for wild pollinator populations. The nutritional status of pollinator populations very clearly interacts with other factors. It is no surprise that bees subjected to nutritional stress are more sensitive to pesticides and for the interaction between both these factors to be synergistic [165–167]. Along these lines, certain works indicate that adequate nutrition can help mitigate the negative effects of pesticides [168,169], which underlines the importance of maintaining an extensive availability of flora resources in agricultural environments. Other studies show that honey bee hives with nutritional stress are more vulnerable to pathogens and have lower survival rates [170,171]. Similarly, many different studies indicate interactions between diseases and sensitivity to pesticides. For example, sublethal doses of certain insecticides affect the immune system of honey bees, making them more vulnerable to attacks from viruses and pathogens, and diseased colonies are likewise more sensitive to insecticides [172–175]. A recent study shows that the impact of viral diseases on honey bee hives is highest in intensive farming areas, with communities depleted of floral resources and with the frequent use of pesticides [176].

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CHAPTER 4
PLANT PROTECTION PRODUCTS

4.1 OVERVIEW

Plant protection products (also called **pesticides**) are used to control pests, disease and weeds in agriculture and, less frequently, in forest and urban environments. The use of pesticides has played an essential role in agricultural intensification, and is considered a key element in the increased yield of many crops. Pesticides also have a series of unwanted effects, such as environmental pollution and its impact on non-target organisms like pollinators and the natural enemies of pests, among many others.

In 1991, the European Union established a legislative framework that regulates and authorises plant protection products and organic production (Section 9.2.7), in order to promote the use of preventive methods and non-chemical methods in plant protection product management. Alongside this, some European regions have favoured integrated production (Section 9.2.6) which prioritises preventive methods and the rational use of plant protection products. Furthermore, the data available from some European countries and from the Member States shows that sales of pesticides have remained the same or have increased since 1990 [1,2], exceeding the figure of 350,000 tonnes per year in the European Union [3]. Spain is one of the top four countries in Europe in the sale of pesticides, although it is also one of the main agricultural producers [3]. Since 2011, the sale of fungicides and herbicides in Spain has experienced a slight increase, whereas that of insecticides has remained stable [4] (Fig. 17).

One of the strategic objectives of the new Common Agricultural Policy [5], of the EU Biodiversity Strategy for 2030 [6] and of the EU *From Farm to Fork* Strategy [7] is a 50% reduction in the use of plant protection products by the year 2030.

TOTAL ACTIVE SUBSTANCES COMMERCIALISED (TONNES)

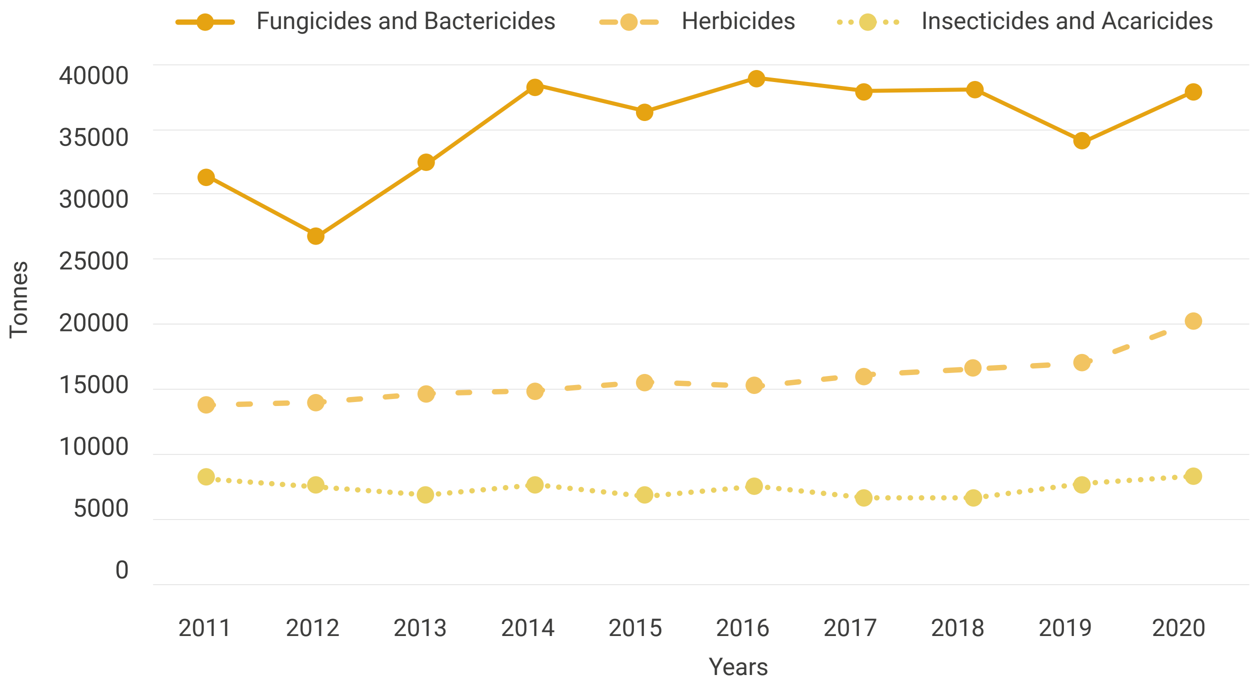

Fig. 17. Pesticide sales in Spain over the past decade. (Source: [4])

4.2 EXPOSURE PATHWAYS

Most plant protection products used in agriculture are dissolved in water for spray (or fog) application. In some crops, however, dry applications (powder) or seed coating (sometimes known as "seed shielding") are also frequent. Other less frequent methods of application include dissolving the product in irrigation water. In Catalonia, dusting is only permitted in certain forestry treatments and in rice fields.

Pollinators can be exposed to pesticides via different exposure pathways, including the ingestion of contaminated pollen and nectar [8]. Other less significant routes of **oral exposure** are honeydew from aphids, fluids from guttation (drops of xylem exuded by the leaves of some plants) and water from contaminated puddles [9,10]. Exposure is also possible by **contact** both with flowers and with other organs of plants, as well as the soil and other surfaces affected by the treatment. Soil exposure can be particularly significant for ground-nesting bees and wasps. Some species that nest in pre-established cavities use mud or different plant products to build their nests (leaves, resin, bud down), so they can also be exposed when collecting or handling these materials. Another significant exposure pathway is contact with the dust generated when planting seeds treated with insecticide [10,11]. This dust can come directly into contact with the pollinators or through flowers.

4.3 TYPES OF PLANT PROTECTION PRODUCTS

In terms of pollinators, pesticides can be divided into three main categories: Insecticides (including acaricides), fungicides and herbicides. Although toxicity for pollinators is, of course, greater in the case of insecticides, it must be noted that the quantities of fungicides (38,000 t) and herbicides (20,000 t) applied in Spain widely exceed that of insecticides (8,400 t) [4].

4.3.1 Insecticides (and acaricides)

Insecticides are substances which kill insects. In order to protect pollinators, the application of most insecticides is forbidden during bloom, and this limitation is indicated on the product label.

Most insecticides are synthetic products and target the nervous or muscular system. Globally, organochlorine pesticides are no longer used, and the use of organophosphate and carbamate insecticides is decreasing. The use of pyrethroids, however, has remained stable since the 1970s, and neonicotinoids have increased greatly since the early 1990s [12]. Available data for Spain shows similar trends [4]. In recent years, however, in light of the accumulated evidence relating neonicotinoids with lethal and sublethal effects in bees [13–15], most neonicotinoids have been banned for use on outdoor crops in the EU, and their use has been restricted in other countries [16,17]. Some insecticides, known as growth regulators, act by affecting the development of insects. This group includes chitin synthesis inhibitors, an essential component in insect cuticles. These insecticides affect the larvae but not the adults and, in general, their use is permitted during bloom. Despite having no effect on adult bees, some studies show that exposure to these products can have a negative effect on egg eclosion [18].

Other insecticides, such as Neem oil or pyrethrins, are natural byproducts. This category also includes the spores of the *Bacillus thuringiensis* bacteria and the toxins they generate, used to control Lepidoptera, Coleoptera and mosquito larvae. Natural, organic insecticides are often less toxic and harmful to the environment than synthetic insecticides, although they can also have negative effects on bees [19].

4.3.2 Fungicides

Fungicides are substances that kill or inhibit the growth of fungi. Most fungicides used in agriculture are synthetic, but some are natural. Their toxicity to bees is much lower than that of insecticides [20]. Their use during crop bloom is therefore permitted. Despite this, some fungicides can synergistically promote the toxicity of certain insecticides, with lethal and sublethal effects on bees. These **synergistic effects** occur primarily when ergosterol biosynthesis inhibitor fungicides are mixed with pyrethroid [21–23] or neonicotinoid insecticides [21,24,25]. It is important to note that bees can be exposed to many different products, despite them being applied separately and at different times. A systemic insecticides (i.e., which penetrates the plant and spreads through its tissues) applied during pre-bloom can appear in the nectar and pollen of the crop and mix with the fungicide applied during bloom, for example. Apart from these synergistic effects with insecticides, some fungicides can, in themselves, affect the behaviour of bees [26,27]. Exposure to certain fungicides, for example, alters the physical and chemical signals of male solitary bees *Osmia cornuta*, reducing their degree of acceptance by females and, therefore, their capacity to mate [28].

4.3.3 Herbicides

Herbicides are substances used to eliminate unwanted plants. Most are synthetic, but there are also some that are natural. In agriculture, herbicides are particularly used to reduce the **competition between the spontaneous flora** and the crop. A recent study shows that bumblebees do not avoid flowers treated with herbicides and, therefore, are exposed to these products both topically and orally [29]. Like fungicides, herbicides have a low toxicity in bees [30]. Despite this, some studies have found that realistic doses of some herbicides affect the learning capacity of the honey bee [27,31,32], and the thermoregulation capacity of bumblebees, which is crucial for correct colony growth [33]. Other studies show that exposure to realistic levels of herbicide affect the gut microbiota of honey bees, increasing the likelihood of pathogen infections [34]. Furthermore, herbicides have a significant, indirect effect on pollinators by destroying floral resources [35] and the foodplants of the larvae of some Lepidoptera, such as the monarch butterfly (Section 3.2). Many of the plants traditionally considered "**weeds**" are an essential source of pollen and nectar for pollinators in agricultural environments (Section 9.2.2).

4.3.4 Other products

There is a series of substances that have no biocide activity but are also used in agriculture, either as part of the formulation of the plant protection product (**co-formulants**) or mixed with insecticides, fungicides or herbicides (adjuvants). Co-formulants are substances used by industry to stabilise and improve some of the properties of plant protection products. Diverse businesses use different co-formulants, and their composition is often unknown. **Adjuvants** are substances that are mixed with the commercial product in the treatment tank to increase the effectiveness of the plant protection product. Both types of substances are considered harmless to bees, although some studies show that certain co-formulants and adjuvants can have sublethal or even lethal effects on pollinators, especially when combined with certain insecticides [26,36–39].

4.4 EFFECTS OF PLANT PROTECTION PRODUCTS ON POLLINATORS

The effects of plant protection products on pollinators depends on both the **toxicity** of the product and the **exposure levels**. A highly toxic product can have little impact on pollinators if its exposure level is low. Likewise, a relatively non-toxic product can have a major impact if its exposure level is extremely high or long lasting. In the case of pollinators, exposure levels are often higher in products applied during bloom, such as fungicides. Therefore, the basic question is whether a product (or mix of products) is toxic for a pollinator at realistic exposure levels. Another factor to consider is the **persistence** of the product. Some products can remain in the atmosphere for months, thus increasing the risk of intoxication due to **chronic exposure** [40].

The effects of plant protection products on pollinators can be lethal or sublethal. Of course, the **lethal** effects are more harmful yet easier to detect, at least in managed pollinators, and this can help in their prevention. Along these lines, it is particularly important to establish a good network of mortality incidents in honey bee apiaries. In countries such as Germany, Holland and the United Kingdom, the number of incidents involving pesticides was seen to have reduced from around 200 to roughly 50 per year between 1980 and 2006 [41,42]. Establishing a direct relationship between an application and an episode of mortality is not always easy, due to product degradation and because, in many cases, chemical analyses reveal the presence of many different residues. Detection of a residue does not necessarily mean that the product in question has had a negative impact. Almost 50% of the bee samples analysed in said studies contain insecticides and 40% fungicides. The instructions on the label must be strictly followed when applying the product to avoid mass intoxications. A study conducted in the United Kingdom concludes that 65–70% of the incidents recorded between 1981 and 1991 were due to inadequate use of the product [43].

Sublethal effects involve the behaviour or the physiology of the pollinator and are more difficult to detect because they do not result in death. Despite this, sublethal effects alter the activity of the pollinator and its reproductive success, so they can have significant consequences on the population. There is a variety of sublethal effects caused by exposure to pesticides, which include enzyme inhibition, immunosuppression, altering of olfactory and visual responses, loss of memory, thermoregulation, collection activity, longevity and fertility [14,44–52]. Some studies have shown that colonies of *Apis mellifera* exposed to pyrethroids or neonicotinoids have a higher rate of workers that do not return to the hive due to a loss of orientation [13,53,54]. Of course, the lethal and sublethal effects of pesticides on pollinators also affects the pollination ecosystem service.

4.5 RELATIONSHIP BETWEEN THE USE OF PESTICIDES AND POLLINATOR DECLINES

There is a certain amount of discrepancy as to how the effects of insecticides in general and of neonicotinoids in particularly can, in themselves, explain the generalised decline of bees. Different reviews on this matter highlight the lack of field studies and the need to establish reliable measurements of **realistic exposure levels** [8,40,63,55–62]. Some of these reviews conclude that the effects found in controlled experiments occur at similar exposure levels or below the real levels at which bees are exposed in the field. Others, however, reach an opposing conclusion. The main reason for discrepancy lies in the lack of agreement as to the determining of realistic exposure levels [59,64]. It is easy to measure the quantity of product applied in a certain area, but it is extremely difficult to determine the fraction of that quantity that ultimately comes into contact or is ingested by pollinators, particularly considering chronic (prolonged) exposure and exposure to multiple products.

Field experiments measure the real impact of pesticides on bee populations, although performing these experiments is complex, especially when working with honey bee colonies that have a flight radius of several kilometres. Along these lines, one study concludes that most field studies involving the honey bee have insufficient statistical power to detect the possible sublethal effects of pesticides [57]. Another study, performed in rapeseed fields sown with neonicotinoid-treated seeds, found no effect on honey bee colonies but instead on the growth of *Bombus terrestris* colonies and, above all, on the nesting of the solitary bee *Osmia bicornis* [15]. Another study conducted in three European countries (United Kingdom, Germany and Hungary) compares the reproductive success of honey bee colonies, *Bombus terrestris* bumblebee colonies, and populations of the *Osmia bicornis* solitary bee in rapeseed fields sown with seeds treated and not treated with neonicotinoid pesticides [65]. The study finds different results depending on the country and on the species. On one hand, the fertility of *Osmia bicornis* and the production of queens in *Bombus terrestris* colonies decreased following exposure to neonicotinoids. On the other, the growth of honey bee colonies was lower in treated fields in the United Kingdom and in Hungary, yet higher in Germany. The differences among species observed in this study can also be explained through three reasons. Firstly, species of the *Osmia* genus are more sensitive to neonicotinoids than honey bees and bumblebees [24,66]. Secondly, different species of bees have different routes and levels of exposure [67]. Lastly, and probably most importantly in this case, social species (bumblebees and, more particularly, the honey bee) are able to curtail the effects of an intoxication thanks to "**colony resilience**". In these species, the death or loss of vigour of several worker bees does not have a major effect on the reproductive success of the colony because it can be offset by other individuals. In solitary bees, however, the death of a female leads to the instant suppression of their reproductive capacity.

Other field studies focused on the relationship between applications of plant protection products and the abundance and richness of pollinator communities at different spatial scales [68]. These studies found negative associations between the richness/abundance of bees and the levels of pesticides in fields of bilberries [69], apples [70] and vines [71]. A study performed in four locations in California monitored over 40 years shows how the use of neonicotinoids has a negative effect on butterfly populations, particularly small species with few generations per year [72]. Other authors also found a negative correlation between the use of pesticides and the quantity of butterflies in an extensive network of gardens in France [73].

4.6 MULTIPLE EXPOSURE

It is important to note that pollinators are often simultaneously exposed to multiple products in agricultural environments. This **multiple exposure** may be due to treatments which mix different products, but also to products applied at different times. As indicated above, residues from systemic products treated during pre-bloom can appear in pollen and nectar [74] and mix with products applied during bloom. This double exposure increases the rick of intoxication because, as explained in Section 4.3.2, some fungicides act synergistically with certain insecticides, increasing their toxicity. Numerous studies have analysed the presence of pesticide residues in the body of bees and in their food [8]. In the United States, a study performed in agricultural environments found averages of 2.5 and 7.1 plant protection products, respectively, in the body of honey bees and in pollen carried to the hive [75]. The products detected include insecticides, acaricides, fungicides and herbicides. A more recent study, also set in agricultural environments in the United States, analysed pesticide levels in the soil, in flowers and in the body of different managed and wild bee species [76]. The study detected 21 plant protection products in the soil samples, 16 in the flora from margins, and 17 in the body of bees, including substances that had not been used to treat that field or adjacent fields. Pesticide levels found in the body of bees were lower than those of flowers, although higher than those of the soil. In another study conducted in meadowland and corn fields, 19 plant protection products were detected in the body of wild bees [77]. Although the concentrations detected are lower, these studies show that pollinators come into contact with a wide variety of plant protection products in agricultural environments. The possible effects of these mixtures of pesticides are yet unknown.

4.7 BEST PRACTICES IN THE USE OF PESTICIDES

Phytosanitary management must following current regulations, which includes only using products that are permitted by law and for the legally indicated uses, applying legally permitted doses and only during the established phenological phases of the plant, and following the safety instructions on the label when applying the product. All treatments must be duly recorded in field books, in accordance with current law. The risk of a phytosanitary treatment to pollinators increases quite significantly if the **information on the label** is not heeded or if this information is insufficient. This is also the case if the machinery used to apply it is inadequate or the treatment is not applied correctly. For example, in post-bloom treatments with insecticides, it is important to wait until the petals have fallen so as not to intoxicate bees. It is also extremely important not to apply treatments in windy weather, which encourages the product to **drift**, and to take general measures to prevent the product from reaching the accompanying flora. Therefore, good training and following best practices during the application process are essential in minimising risks [78]. Different studies have shown that ruderal plant species growing near fields contain significant levels of plant protection products [11,76,79,80].

4.8 RISK ASSESSMENT

Prior to their authorisation, plant protection products must be subjected to a long risk assessment process designed to ensure their use will not involve **environmental risks**. This assessment includes a series of laboratory, semi-field and field toxicity tests with the honey bee [81]. Risk assessment programmes are essential in protecting bees and other pollinators, and are updated as new assessment methods are refined.

Even so, these programmes have certain shortfalls, such as insufficient coverage of **chronic exposure** (as opposed to acute), exposure to **product mixtures** and the detection of **sublethal effects** [16]. Another aspect to be improved upon is the inclusion of other bee species, such as bumblebees (*Bombus terrestris*) and solitary bees (*Osmia* spp.) when assessing risk, as recommended by the European Food Safety Authority [82]. Due to differences among species in their sensitivity to different products [24,83], o differences in the biological traits determining the routes and levels of exposure [67], and colony resilience, the results obtained with the honey bee cannot always be extrapolated to other bee species.

4.9 USE OF PESTICIDES IN NON-AGRICULTURAL SYSTEMS

Although most pesticide treatments are applied in agricultural environments, their use in forest areas and in urban and peri-urban zones must also be considered.

Treatments in **forest environments** are particularly applied to control species of Lepidoptera and Coleoptera, which can become significant pests. In Catalonia, biological treatments with *Bacillus thuringiensis* are commonplace to reduce the impact of the pine processionary, *Thaumatopoea pityocampa*, a moth species which not only weakens pines but can also cause severe hives in humans due to the toxic hairs released by its caterpillars. Treatments are commonplace and affect thousands of hectares in central Catalonia, although they are also applied to a lesser extent near inhabited areas to minimise the discomfort that the caterpillars cause in humans and pets. These treatments have also been occasionally applied to combat outbreaks of the gypsy moth caterpillar, *Lymantria dispar*, in the forests of the Montnegre mountain range, for example. The use of treatments to control *Lymantria dispar* has been questioned due to their lack of effectiveness and to its control by its natural enemies, which reduce the pest to harmless levels within 1 to 4 years. These treatments have also been criticised due to their impact on other non-target Lepidoptera [84].

Pesticides are, in theory, used much less often in **urban environments** than in areas of agricultural production. Even so, use of these products in public and private gardens and vegetable plots is not insignificant. In the United States, it has been calculate that the use of herbicides, insecticides and fungicides in urban areas accounts for 8%, 15% and 10%, respectively, of the total amounts used in the country [85]. It is therefore hardly surprising to find residues of different plant protection products in the nectar and pollen of flowers in urban gardens [86]. One study in France concludes that certain treatments in private gardens may have an impact on butterfly and bumblebee populations [87]. No data is available in Catalonia on the use of plant protection products in urban environments. It must be noted, however, that the use of pesticides in private gardens and vegetable plots for family consumption is not overly regulated. Different pesticides can be purchased by customers with no kind of training in their use from internet stores and e-commerce platforms. A recent study in the United Kingdom indicates that, following the moratorium on the use of certain neonicotinoids, exposure levels of bumblebees have decreased in rural areas but not in peri-urban areas [88]. The use of pesticides in urban environments and in private gardens and vegetable plots is much harder to justify than in agricultural operations. To this end, there are different initiatives in place throughout Catalonia to drastically reduce the use of pesticides in the management of public and private green spaces.

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CHAPTER 5
CROP POLLINATION IN CATALONIA: DEFICITS AND STRATEGIES

5.1 POLLINATION DEFICITS

As explained in Section 1.7, many crops depend on insect pollination to reach financially viable production levels. Some agricultural practices, however, particularly those associated with intensive farming, have a negative impact on pollinator populations (Section 3.1). Therefore, particularly in mass-flowering crops producing many flowers over a short period of time, there might be insufficient wild pollinator populations to provide an adequate pollination service. In the event of such, it is important to promote pollination by either encouraging wild pollinator populations or by providing managed pollinator populations (Section 5.2). The decision to promote pollination is often based on the insight of the grower and on their prior knowledge of the specific crop and its variety. Ideally, whether there is actually a **pollination deficit** (Section 1.2; [1]) and whether this significantly affects the yield and/or quality of the crop should be ascertained.

5.2 POLLINATION STRATEGIES: WILD POLLINATORS AND MANAGED POLLINATORS

Entomophilous crops attract a series of **wild pollinators** which naturally visit and pollinate their flowers. Despite the fact that this ecosystem service has traditionally been considered insufficient to ensure adequate pollination levels that remain stable over time, there is an increasing number of studies to show the extremely significant contribution to agricultural production by natural pollinator populations, which is sometimes comparable or even superior to the contribution by managed pollinators [2]. Therefore, encouraging natural pollinator communities to establish their habitat in fields could be a financially profitable strategy. The measures taken to promote natural pollinator populations are explained in Chapter 9, and the importance of a functionally diverse pollinator community with a high degree of complementarity is explained in Section 1.7. Generally, wild pollinator populations are much less abundant than those of managed pollinators, although this is often offset by their significant pollination effectiveness [3]. There is increasing scientific evidence on the positive effects of the diversity and abundance of wild pollinators in the yield and quality of crops [4–8].

The decision to provide **managed pollinator** populations in a certain field or area should only be made when there is seen to be a pollination deficit. Pollination deficits occur particularly in areas of intensive farming, with typically depleted natural pollinator communities, large fields, and little crop diversity. The agricultural intensification process over the past century has meant that the use of managed pollinators is a relatively common practice which remains on the rise [9,10]. As explained (Section 3.9), the use of managed pollinator populations could lead to certain risks for wild pollinators. Furthermore, dependence on a single pollinator species also involves a loss of functional diversity that could negatively affect the pollination function (Section 1.8). On all accounts, the recommended densities of managed pollinators, whether honey bees, bumblebees or solitary bees, should always be provided [11].

A mixed strategy could also be applied, combining the use of managed species with the promoting of a diversity of natural pollinators in agricultural environments [2]. This strategy could include the use of more than one managed species. In this case, however, the density of each species should be reduced so as not to limit floral resources, which would endanger the sustainability of wild pollinator populations.

5.3 EVALUATION OF INSECT POLLINATION OF CROPS IN CATALONIA

As is the case worldwide, insect pollination is a key ecosystem service for agricultural production in Catalonia. Figure 18 shows the cultivated area and agricultural production of the different groups of crops in Catalonia. The crops occupying most land include cereals (43%), olives (14%) and vines (7%), which do not depend on insect pollinators. Crops which do depend on pollinators include **fruit trees** (particularly the almond, but also the cherry, apply and pear) which have remained more or less stable in Catalonia over the past five years, occupying 14% of the cultivated land [12]. Other crops which depend on pollination include certain **legumes** (e.g., French bean, broad bean; 1%), **fruit and vegetables** (tomato, melon, watermelon, strawberry; 1%), and some **industrial crops** (rapeseed, sunflower; 2%). The total area of rapeseed grown as an alternative to the traditional monoculture of winter cereals has increased significantly in Catalonia over recent years (from 8,710 ha in 2014 to 12,658 in 2020; [12]). **Forage crops** (including alfalfa, sainfoin or vetch), which occupy a large total area in Catalonia (17%) must also be mentioned. Although most of this total area is dedicated to forage production and, therefore, does not require pollination, the seed used to sow the fields depends on insect pollination. Insofar as production, forage crops account for 50% of the total in Catalonia (Fig. 18).

Table 1 shows the list of entomophilous crops in Catalonia, their total area and production, and their **degree of dependence** on insect pollination, according to the FAO [13]. It must be noted that this degree of dependence varies greatly depending on the variety and, therefore, estimations are merely illustrative. In terms of cultivated hectares, fields of almond (39,424 ha), peach/nectarine (19,293 ha), pear (9,687 ha) and apple (9,272 ha) trees are worth highlighting. In terms of production, apple trees yield the most crop (235,434 t), followed by peaches (202,499 t), nectarines (140,183 t) and pears (138,044 t) [12]. Catalonia also produces over 200.000 tonnes of vegetables a year on more than 9,500 hectares, representing the most commercially productive crop group after fruit trees. Approximately 40% of all vegetable crops depend on insect pollination to some extent [12]. Some of these, such as the pumpkin, courgette, melon or watermelon, are highly dependent on insect pollination [13].

It is important to note that the market price of crops which depend on insect pollination is an average of five times higher per tonne than non-dependent crops [14]. The **value of crop pollination** by insects is calculated to stand at around 290–321 million euros [15,16]. These are conservative amounts, as they are calculated considering the average value of the level of dependence on pollination of each crop and only consider crops that are for direct human consumption, which means they do not include forage crops, meadowland and family vegetable plots. The fruit sector in Catalonia generates over 980 million euros a year [17,18].

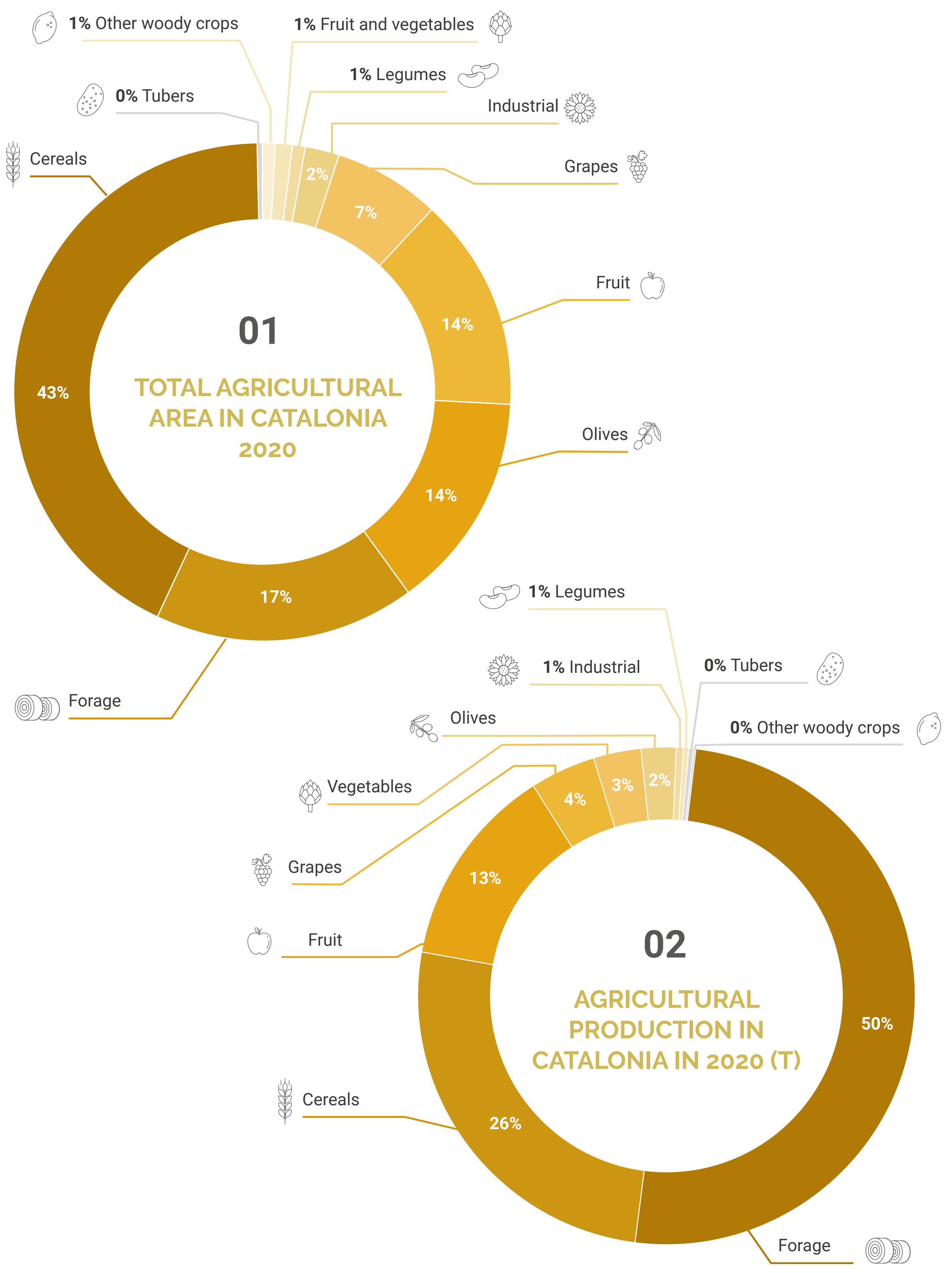

Fig. 18. Total area in hectares (**01**) and production in tonnes (**02**) of the main crops in Catalonia. (Source: [12])

CROP	TOTAL AREA (Ha)	PRODUCTION (T)	DEGREE OF POLLINATOR DEPENDENCE (%) (FAO)
CITRUS FRUIT TREES			
Orange	2180	43546	0–10
Mandarin	6585	135601	0–10
Lemon	31	152	0–10
Grapefruit	1	0	0–10
FRUIT TREES			
Kiwi	61	835	>90
Apple	9272	235434	40–90
Pear	9687	138044	40–90
Medlar	1	11	40–90
Apricot	1885	9399	40–90
Cherry	2771	8127	40–90
Peach	10541	202499	40–90
Nectarine	8752	140183	40–90
Plum	395	4669	40–90
Avocado	6	36	40–90
Almond	39424	25840	40–90
Bilberry	2	8	40–90
Raspberry	2	18	40–90
Fig	556	5834	10–40
Pomegranate	137	1723	10–40
Chestnut	101	43	10–40
Redcurrant	2	16	10–40
Quince	103	1278	0–10
Persimmon	119	1782	0–10
FRUIT AND VEGETABLE PLANTS			
Watermelon	267	7597	>90
Melon	244	4730	>90
Pumpkin	411	10984	>90
Courgette	263	8201	>90
Cucumber	177	9506	40–90
Turnip and others	101	1816	40–90
Fennel	81	1620	40–90
Aubergine	126	3275	10–40
Pepper	183	4517	10–40
Chilli pepper	10	158	10–40
Strawberry	64	1964	10–40
Green pea	254	1189	10–40
Broad bean	303	2994	10–40
Tomato	1029	42684	0–10
French bean	384	6320	0–10
INDUSTRIAL			
Sunflower	2724	5652	10–40
Rapeseed	12658	27417	10–40

Table 1. Total area, production and degree of dependence of insect pollination of crops in Catalonia. (Source: [12.13]).

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CHAPTER 6
IMPROVEMENTS IN POLLINATOR KNOWLEDGE

In producing this report, a series of shortfalls in the knowledge of pollinators in Catalonia (and sometimes globally) were identified, which are discussed in detail in this chapter.

6.1 POPULATION DISTRIBUTION, STATUS AND TRENDS OF WILD POLLINATORS IN CATALONIA

The CBMS (www.catalanbms.org) has provided high quality information in Catalonia on diurnal butterfly populations, which has been used to highlight the negative population trends of many species and offer a good scientific basis for establishing their conservation status. Unfortunately, this type of information does not exist for other pollinator groups. Of particular relevance is the lack of a **catalogue** of **bee and syrphid** species, and information on their population trends. Coleoptera are an especially well studied group in terms of taxonomy and fauna in Catalonia, although there is also no information on their population trends. Establishing a **programme to monitor** the pollinator populations in Catalonia and producing catalogues and distribution maps of the main pollinator groups (bees and syrphids) are a priority in solving this limitation. Another critical line of research would be the comparison of population trends in areas located within and outside protected areas in order to assess whether or not they are being adequately managed for pollinator conservation.

6.2 USE OF PLANT PROTECTION PRODUCTS AND ASSESSMENT OF RESIDUE LEVELS

In agricultural environments, bees are subject to more or less critical **exposure** to different plant protection products. There is, however, very little information on the actual levels of this exposure. A recent report produced by a European Court of Auditors to assess whether the European Union is reducing the use of plant protection products indicates that sales of these products have remained stable over the past ten years [1]. The report also highlights the lack of detailed records and statistics on plant protection products, which hinders the strict analysis of data and comparisons between years and areas. Along these lines, it is important to establish a programme to monitor the **residue levels** to which bees are exposed. This monitoring could involve a network of sampling points where multi-residue analyses of different matrices related to bees (flowers, soil, honey, pollen) or of the bees themselves are performed.

6.3 RISK ASSESSMENT OF PESTICIDES

The risk assessment prior to the commercialisation of any pesticide is an essential process for pollinator protection, as it determines the conditions in which a product can be used. The risk assessment must therefore be as thorough as possible. Certain aspects to improve upon include greater coverage of **chronic exposure**, the assessment of certain **product mixtures**, an increase in the tests on **sublethal effects**, and the **inclusion of other pollinator species** apart from the honey bee.

6.4 BOOSTING ECOSYSTEM SERVICES IN AGRICULTURE

Despite calls from different authorities to reduce pesticide dependence, the use of these products has not decreased over recent decades. One argument often used to justify the use of pesticides is based on the claim that production is lower when the application of plant protection products is drastically reduced. Likewise, phytosanitary management systems with a lower pesticide load, such as organic or integrated production, have less of an impact on the environment. Therefore, a critical line of global research should be the study of strategies to **improve the productivity** of agricultural systems based on the promoting of ecosystem services (**organic intensification**) and on the use of species and varieties that require a lesser amount of plant protection products.

6.5 BEEKEEPING CARRYING CAPACITIES

The installation of large numbers of honey bee hives is of growing concern among managers of nature reserves and other protected areas in Catalonia and throughout Europe. Assessing the carrying capacity of a landscape is a complex task, yet it is a necessary measure to establish density thresholds to ensure honey production is compatible with pollinator conservation.

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CHAPTER 7
CONCLUSIONS AND KEY MESSAGES

The following conclusions and key messages can be taken from all the information provided in the diagnosis of the status and trends of insect pollinators and the analysis of the main threats affecting them:

- Insect pollination is an essential ecological process that is crucial for the formation of fruit and seeds in many plants and for ecosystems to function properly. In addition to plants, many animals depend indirectly on this process.

- Insect pollination is also a vital ecosystem service for the health and well-being of mankind. 75% of all plant species cultivated around the world to feed human populations depend on insect pollinators to produce fruit and seeds.

- Scientific evidence indicates that insect pollinators are suffering an unprecedented, extremely concerning decline worldwide. This trend is also seen in Catalonia through the monitoring of butterfly populations. Information on population trends of other important pollinator groups (flower-visiting bees, Syrphids, and Coleoptera) is almost non-existent in Catalonia.

- Insect pollinator declines lead to a reduction in their abundance, diversity of species and functional diversity. A loss of functional diversity results in the reduced resilience of natural and agricultural systems against the environmental imbalances motivated by the change of land uses and climate change.

- There are many reasons for insect pollinator decline which often interact sinergistically. Agricultural intensification is probably one of the factors to have most contributed to this decline. Intensive farming involves a more intensive use of the land at the expense of natural habitats, and is based on a series of practices that leads to a decrease in the abundance and continuity of floral resources, alters the nesting substrates of many pollinators, and brings about a rise in the environmental load of toxic products.

- Climate change is another very significant cause, although there is insufficient research into its effects on the population. Different studies have recorded changes in the distribution areas of bumblebee and butterfly populations, which are displaced in both latitude and altitude in search of colder zones. Other studies have recorded alterations to the life cycle of some pollinators and changes in their flight periods, which could result in imbalances in the flowering period of the plants they visit.

- Other important factors are urban development, the loss of open spaces due to the eradication of forest habitats (afforestation) and, in the case of managed pollinators, the arrival of exotic parasites and pathogens. Beekeeping intensification tends to homogenise pollinator communities and could result in them competing for floral resources with wild pollinators.

- The European Union has established a legal framework which regulates and authorises plant protection products, prioritising integrated production and organic production. Likewise, pesticide sales in the European Union since 2011 have remained stable at around 350,000 tonnes per year. One of the strategic objectives of the new Common Agricultural Policy (CAP), of the EU Biodiversity Strategy for 2030 and of the EU From Farm to Fork Strategy is a 50% reduction in the use of chemical pesticides by the year 2030.

- As is the case worldwide, insect pollination is a key ecosystem service for agricultural production in Catalonia. Fruit-producing trees (764,000 tonnes per year) with a higher degree of dependence on pollinators include many varieties of almond, cherry, apricot and plum, followed by apples and pears.

- Other important crops in Catalonia which depend on pollinators are rapeseed and sunflower (33,000 tonnes per year). The total area of rapeseed has risen considerably over recent years. 40% of all fruit and vegetable crops (200,000 tonnes) also depend on insect pollination. Some of these, such as the pumpkin, courgette, melon or watermelon, are highly dependent. On average, the market price of crops which depend on insect pollination is higher than non-dependent crops.

PART TWO

PRIORITY AREAS OF ACTION AND MEASURES FOR THE CONSERVATION OF WILD POLLINATORS IN CATALONIA

Male solitary bee *Eucera cineraria* spending the night attached to a sainfoin flower. (Photograph: J. Compte).

CHAPTER 8
IDENTIFICATION OF PRIORITY AREAS AND OBJECTIVES OF ACTION

The Natural heritage and biodiversity strategy of Catalonia 2030 foresees the drafting of an **Intersectoral plan for the conservation of wild pollinators** to respond to the loss of biodiversity leading to insect pollinator decline, for which this diagnosis is the basic premise. This section offers a proposal of the priority areas of action on which the Plan should focus.

The proposed **priority areas** are drafted in accordance with the results of the diagnosis and with the findings of national and international strategic reports and instruments on the conservation of wild pollinators which have been published to date:

- The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [1]
- EU pollinators initiative [2]
- EU Biodiversity Strategy for 2030 [3]
- National Strategy for the Conservation of Pollinators [4]

IPBES assessment report

The report published in 2016 by the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services** assesses the changes occurring worldwide in pollinator populations and their causes. It addresses the consequences of these changes on plant–pollinator interaction networks, the pollination of wild plants, and pollination services, along with the impact on food production and human well-being. The report points to the main political responses that should be given to pollinator declines and pollination deficits from decision-making in government, the private sector and civil society.

Bases on the IPBES report, a group of scientists published ten recommendations for authorities interested in promoting pollinator protection plans [5]. The **ten recommendations**, selected, at least partly, for their feasibility, are:

1. Raise pesticide regulatory standards.
2. Promote integrated pest management.
3. Include indirect and sublethal effects in GM crop risk assessments.
4. Regulate movement of managed pollinators.
5. Develop incentives to help farmers benefit from ecosystem services instead of pesticides.
6. Recognise pollination as an agricultural input in agricultural extension services and technology transfer activities.
7. Support diversified farming systems.
8. Conserve and restore "green infrastructure" (a network of habitats that pollinators can move between) in agricultural and urban landscapes.
9. Develop long-term monitoring of pollinators and pollination.Fund participatory research on improving yields in organic, diversified, and ecologically intensified farming.

EU pollinators initiative

The **EU pollinators incentive**, published by the European Commission on 1 June 2018, strives to help speed up reaching the EU goal of stopping and reversing the loss of pollinator diversity and the pollination ecosystem service in response to the calls for action from the European Parliament and the Council for the protection of pollinators and their habitats. In accordance with this framework, the initiative sets three priorities to define goals and measures:

Priority I: Improve knowledge of pollinator decline, its causes and consequences.

Priority II: Tackle the causes of pollinator decline by managing policies.

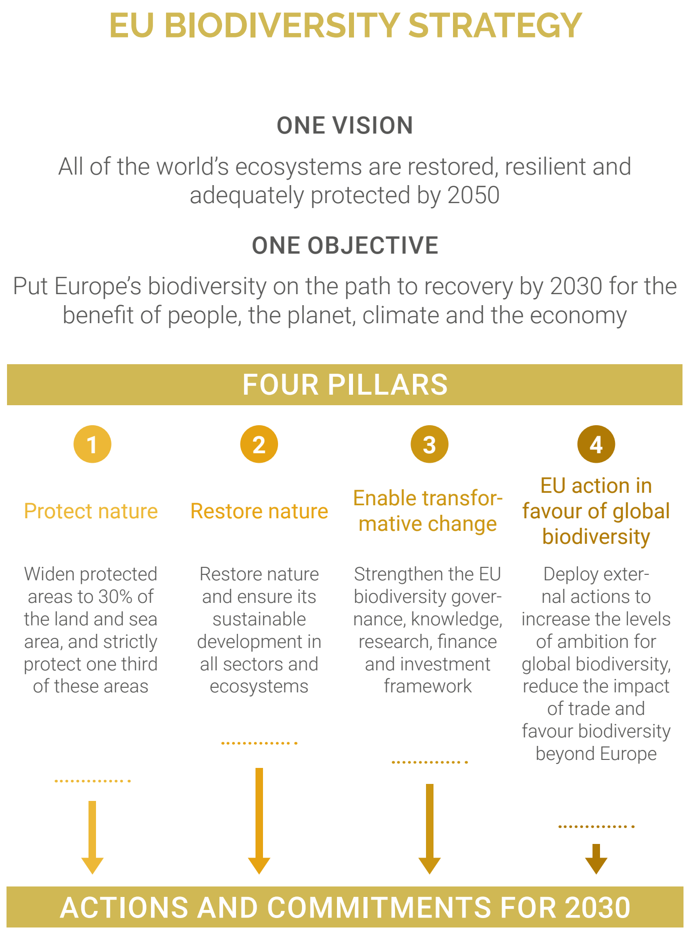
Priority III: Raise awareness, mobilise society and promote cooperation.

The three priorities were defined to help meet the goals of the EU Biodiversity Strategy for 2020 and of sectoral policies such as the common agricultural policy and the cohesion policy. They are also subject to the new EU Biodiversity Strategy for 2030. Furthermore, implementation of these priorities must provide valuable information on the progress made by the EU in meeting the UN Sustainable Development Goals.

The initiative must work in synergy with the action plan for nature, people and the economy and, more specifically, with future directives on green infrastructure in the EU and integration of ecosystem services in decision-making processes. The initiative is also foreseen to have an impact on the new post-2020 multiannual financial frameworks.
EU Biodiversity Strategy for 2030

The new **UE Biodiversity Strategy** for 2030 sets out a vision for the year 2050 in which all the ecosystems in the world have been restored, are resilient and are adequately protected. Along these lines, the objective of the EU for 2030 is to put Europe's biodiversity on the path to recovery for the benefit of people, the planet, climate and the economy. To achieve this, the Strategy sets out **39 specific commitments and targets**, grouped into **4 pillars**, and **37 key actions** which must be specifically implemented by the European Commission.

Among the specific commitments and targets of pillar 2 regarding the restoring of nature in Europe is the target of reversing pollinator decline. In line with this target, the Commission will guarantee full implementation of the pollinator initiative in the EU by developing actions to improve knowledge of the causes and consequences



of the decrease in pollinators and to address them. The Commission will also focus on raising awareness and mobilising citizens, and on promoting cooperation among all stakeholders.

The key actions to be implemented by the European Commission include the need to review the EU pollinator initiative, which is currently underway.
National Strategy for the Conservation of Pollinators

In line with the commitments assumed by Spain, as a member of the International Coalition of the Willing on Pollinators as part of the United Nations Convention on Biological Diversity and within the framework of the European Pollinator Initiative, the **National strategy for the conservation of pollinators** was drafted and subsequently approved by the Sectoral Environment Conference at its meeting of 21 September 2020.

The Strategy first gives a diagnosis of the situation and trends of pollinators and the main causes for their decline. It sets 6 goals based on this diagnosis:

– **Goal A.** Conserve threatened pollinator species and their habitats.
– **Goal B.** Promote favourable habitats for pollinators.
– **Goal C.** Improve pollinator management and reduce risks from pests, pathogens and invasive species.
– **Goal D.** Reduce the risk of the use of plant protection products for pollinators.
– **Goal E.** Support research to improve knowledge.
– **Goal F.** Guarantee access to information and raise awareness on the importance of pollinators.

To meet these goals, the Strategy defines **37 measures to be implemented by 2027**. The summarised list of measures can be referred to in the Annex to the Strategy [4].

When drafting the Strategy, the practical actions taken as part of different present and future sectoral policies which in some manner contribute towards the conservation of pollinators were identified. The strategy also sets out other actions to supplement and improve them.

Using the findings and goals of these documents, and considering the key players that could play a decisive role in the conservation of pollinators, the Intersectoral plan for the conservation of wild pollinators in Catalonia should set **priority goals** and measures in the following areas:

1) Improved knowledge
- Improve knowledge of the conservation status of wild pollinators
- Improve knowledge of the causes of wild pollinator decline

2) Agricultural and food production environment
- Increase best practices in agriculture to favour the conservation of wild pollinators
- Promote favourable habitats for pollinators in the agricultural environment
- Improve pollinator management and reduce risks from pests, pathogens and predators

3) Urban and peri-urban environment
- Promote favourable habitats for pollinators in the urban environment
- Incorporate the conservation of wild pollinators into the management of green spaces and of urban and peri-urban parks
- Take measures to favour pollinator populations in environments associated to transport infrastructure, energy and other services

4) Reduced use of plant protection products
- Identify and reduce the harmful effects of plant protection products
- Reduce the risk to pollinators from plant protection products in agriculture
- Reduce the risk to pollinators from plant protection products in urban environments and major infrastructure

5) Beekeeping and wild pollinators
- Ensure compatibility between beekeeping and the conservation of wild pollinators

6) Society and entities
- Raise awareness on the importance of pollinators
- Encourage participation in pollinator conservation measures
- Guarantee access to information on pollinators and pollination

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CHAPTER 9
MEASURES AND BEST PRACTICES FOR THE CONSERVATION OF WILD POLLINATORS

Based on the knowledge available, certain measures and best practices to ensure the conservation of wild pollinators [1,2] are indicated below.

9.1 PRACTICES TO BENEFIT POLLINATORS IN PROTECTED NATURAL ENVIRONMENTS

32.8% of Catalonia form protected areas of nature, including an extensive group of protective figures, the objective of which is to conserve biodiversity and ensure the use of resources and the activity of their inhabitants are compatible with this objective. Although this should ensure the conservation of pollinator populations, there are many examples of **species which have recorded a significant decline**, even local extinctions, after a protected area has been declared . One paradigmatic case is that of the large blue (*Phengaris arion*), a butterfly which is protected by the **Habitat Directive.** In the early 2000s, this species disappeared from the Montseny Nature Reserve and protected area of the Natura 2000 network, which formed one of the southern limits of this butterfly in Europe. The reasons for these extinctions are possibly related to the droughts of recent decades, although also to the **eradication of their habitat** following the spread of forest land due to pastoral abandonment. This problem is affecting the populations of many other butterfly species in protected areas of the country [3] and is depleting bee communities in forest environments [4]. Historically, clearings of open habitat were created and maintained through low-intensity farming activities such as traditional grazing [5], small extensive farming operations [6] and a low degree of forestry development [7]. Implementing management measures could help reverse the loss of these habitats. Other measures to favour pollinators in protected areas include regulating honey bee hive densities and restricting visits by people to areas of particularly fragile plant life (Section 3.10).

9.2 PRACTICES TO BENEFIT POLLINATORS IN AGRICULTURAL ENVIRONMENTS

9.2.1 Overview

Agriculture takes up 25% of the total area of Catalonia. As explained in Chapter 3, agricultural intensification is considered one of the main factors of pollinator declines. The negative consequences of **agricultural intensification** on the environment and the growing demand for food mean that alternative models of agricultural production must be considered. Over the past decade, a new approach to agricultural production known as **ecological intensification**, as opposed to agricultural intensification, has been defined. Ecological intensification is based on the integration of ecosystem service management into production systems in order to maintain production levels, increase the resilience of agricultural systems, and minimise the negative impacts of agriculture on the environment [8,9]. Along these lines, ecological intensification promotes practices which encourage a series of ecosystem services such as pollination, biological pest control, and improved soil properties. On a local scale, these practices include a more limited use of plant protection products, crop diversification and rotation, a reduction in field sizes, the implementation and maintaining of plant cover, and the establishing of semi-natural habitats in the form of unploughed margin areas, among others. In terms of the landscape, it includes an increase in areas of nature, which ultimately act as a reservoir of biodiversity. Ecological intensification is a priority approach in countries where agricultural production has already reached maximum levels and it is necessary to reduce the environmental costs and the negative pressure applied to ecosystem services.

Since the early 1990s, reforms to the objectives of the **Common Agricultural Policy (CAP [10])** have included a reduction in the pressure of agriculture on ecosystems and, with this purpose in mind, EU Member States have been provided with funding to implement different agri-environmental instruments and **measures.** The latest reform to the CAP, which is to be applied for the 2023–2027 period, reinforces environmental attention and climate action yet further [11]. To this end, the **CAP Strategic Plan** presented by Spain proposes three environmental goals: to contribute towards adaptation to climate change and its mitigation, to promote the sustainable development and efficient management of natural resources, and to help stop and reverse the loss of biodiversity, promoting ecosystem services and conserving habitats and landscapes [11]. To meet the goals of the CAP Strategic Plan, different mechanisms (strengthened conditionality, eco-schemes, sectoral programmes and rural development measures) have been organised, some of which propose actions which have a direct or indirect impact on the protection of pollinators. These actions include crop rotation, the promotion of alternative systems to chemical control for phytosanitary management, and the creation of fallow land. Also included are the creation of protective borders on river banks where no fertilisers or plant protection products are applied, and pastoral management to avoid excessive land erosion, along with the establishing of multifunctional margins, using part of the property for non-productive purposes (hedges, isolated trees, islands of vegetation) and the banning of stubble burning. In short, with the involvement of farmers and other land managers, these programmes seek to provide an environmental service to society as a whole by introducing and maintaining agricultural practices which help protect and improve natural resources, the land and genetic diversity, and mitigate climate change. In Catalonia, the Rural Development Programme (RDP [12]) promotes alternative systems to chemical control, integrated production, fertilisation management and crop diversity, and beekeeping as a measure to improve biodiversity [13].

The success of the proposed measures in all these programmes will mostly depend on their degree of application. Some biodiversity conservation organisations believe that some of the eco-schemes proposed are insufficient to meet the environmental goals posed and that certain sectors might have difficulties in obtaining the grants designed to encourage these practices [14,15].

9.2.2 Crop diversity, spatial configuration and floral resources

The monoculture of entomophilous crops provides a large quantity of floral resources, although these are not overly diverse and last for a very short time. Under these conditions, only a few pollinator species with the same phenology as the flowering of the crop will be able to prosper. In terms of the landscape, there is a positive correlation between the **diversity of crops** and the diversity of pollinators [16]. Apart from the **floral resources** which the crops may provide, the spontaneous flora which grows in the margins and pathways of agricultural environments also helps diversify the range of flowers (Fig. 19). So-called "weeds" are an extremely important source of pollen and nectar, and their presence clearly favours pollinators [17–19]. Some studies show that the abundance and diversity of pollinators increase in areas with small fields and with a high density of well structured margins [16,20–22]. Margins not only provide floral and nesting resources but also act as corridors to favour the movement of insect pollinators. The plants in margins and spontaneous flora in general also play an essential role in attracting and providing food for many natural enemies of pests [23]. Managing these margins correctly is therefore extremely important. The use of herbicides should be avoided, and the cutting frequency and seasonality should be planned so that not all floral resources and foodplants for caterpillars are eliminated at once. Despite their contribution to promoting pollinator populations, these actions are extremely localised. One step further is the establishing of fallow land (fields which are not cultivated for one cycle or more) and waste land (abandoned fields where plant life is left to prosper), and the **restoring and conservation of semi-natural and natural areas** near areas of cropland (Fig. 20).

Fig. 19. Margins of spontaneous flora. (**01**) Margin of a rapeseed field with white rocket (*Diplotaxis erucoides*). The rocket starts flowering before the rapeseed, and helps maintain the pollinator populations visiting the rapeseed. (**02**) Margin with ruderal grass in an organic wine estate (Photographs: A. Martínez-Olalla i M. A. Fuentes).

Fig. 20. Areas of natural or semi-natural plant life near crops. These habitats acts as a reservoir of biodiversity and are essential in maintaining rich and abundant pollinator communities. (**01**) Lowland meadow with a floodable area and irrigated forage crop in the background; (**02**) wet mountain meadow used as swath and grazing land; (**03**) dry meadow with therophytes and scrub of rock rose and wandering heath near a cork oak grove; (**04**) flowering false brome thicket in an abandoned field; (**05**) Mediterranean scrub with rock rose. (Photographs: M. A. Fuentes (**01**, **02**, **03**), S. Pérez-Segú (**04**), N. Vicens (**05**)).

9.2.3 Ecological infrastructures to promote floral resources

The availability of **floral resources** can also be actively promoted through either hedgerows or flower strips. Hedgerows use woody plants to create barriers which act as a windbreak or to encourage the natural enemies of pests [24]. These hedgerows favour the presence of prey and hosts which attract predatory insects and parasitoids such as syrphids and different groups of wasps, thus helping maintain the communities of these natural enemies and, therefore, promote the biological control of crop pests [25,26]. The inclusion of trees or bushes which produce entomophilous flowers in these hedgerows also provides floral resources which are used as food for the adults of these natural enemies and for many pollinators, as well as trophic resources for the larvae of many Lepidoptera [27].

Similarly, maintaining flower strips on either the edges or the insides of fields has proven extremely effective in encouraging natural enemy and pollinator populations [28–31]. The availability of seeds from wild plants is increasing and seed mixtures are starting to be commercialised. It is important to always sow native and preferably local species which, overall, provide continued bloom to ensure there are no periods when flowers are unavailable. In the case of entomophilous crops, it is particularly important to provide resources before the field blooms to help support the pollinator populations visiting the crop. It is also important for the mixture to include the widest range possible of families of plants and flower types so as to encourage pollinator diversity. Of course, the effectiveness of these agro-ecological infrastructures depend on correct maintenance to prevent them from interfering with other agricultural practices. Among others, it must be noted that flower strips may be affected by phytosanitary treatments [32] and, therefore they could act as traps for pollinators.

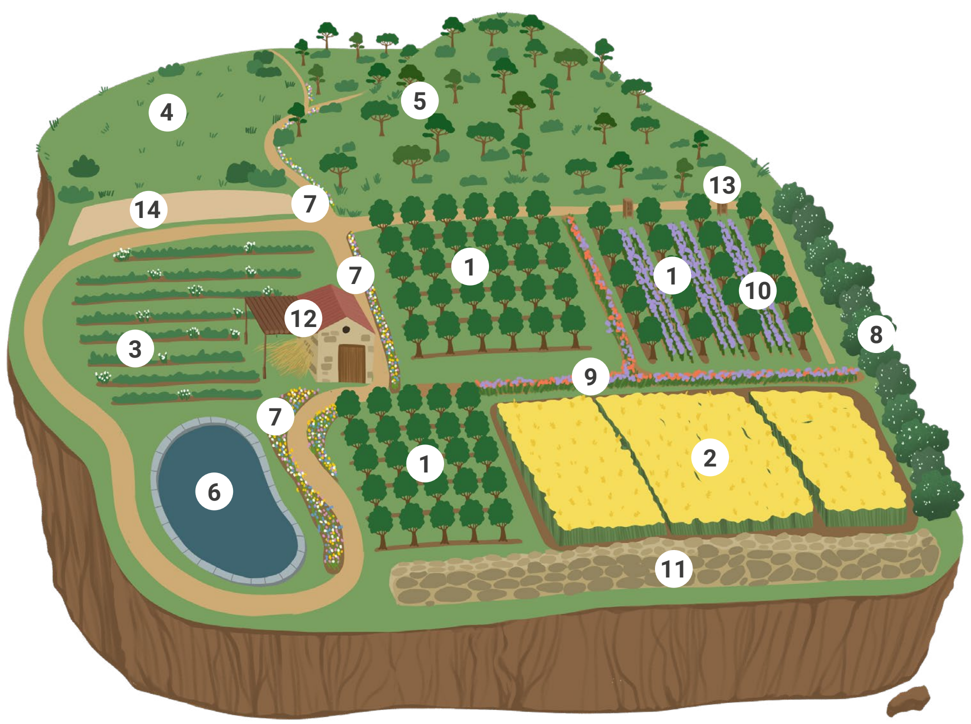


Fig. 21. Farm favourable for pollinators, with a mosaic structure comprising different crops (fruit, rapeseed, vegetables) (1,2,3), fallow land (4), an area of natural plant life (5) and a pond (6). The margins with spontaneous ruderal plant species (7), the hedgerow (8) and the sown flower strips (9), as well as the co-cultivation of legumes (10) and the thickets of alyssum, *Lobularia maritima*, (3) provide diverse, abundant floral resources. This plant life also ensures the spread of syrphids and other natural enemies of pests. The dry stone wall (11), the building with stone or adobe walls, wooden beams and cane roof (12); and the insect hotels (13) offer nesting areas for cavity-nesting bees. The area of bare land (14) encourages the nesting of ground-nesting bees.

The effectiveness of the agri-environmental measures depend on the context in which they are applied, in terms of both intensity and configuration of the landscape and field management [33,34]. Sowing flower strips in fields where there are already a lot of floral resources will not have the same effect, for example, as in fields where the destruction of margins or the use of herbicides has eliminated the accompanying flora [35]. Likewise, no longer using pesticides in a field will have different effects on pollinators, depending on the treatments applied in the surrounding fields [36].

9.2.4 Nesting substrates

Bee and wasp populations depend not only on floral resources but also on **nesting resources**. It is therefore necessary to respect any nesting substrates around the properties, such as areas of bare land, clay slopes, and dead tree trunks (Fig. 22). Old buildings, with stone walls, wooden beams and cane roofs provide many different cavities in which different solitary bees and wasps can nest (Fig. 22). Adobe walls and dry stone walls are particularly interesting in this respect. Nesting substrates can also be actively created for

Fig. 22. Wild bee nesting substrates. (**01**) *Lasioglossum* nests (similar to anthills) in a dirt track; (**02**) Shear clay wall containing *Anthophora* nests; (**03**) Tree stump containing xylophagous coleoptera holes used by *Osmia*, *Megachile*, *Hoplitis* and other cavity-nesting bees. (**04**) Old building with different types of cavities (cracks between stones, holes in beams, canes) where these species also nest. (Photographs: N. Vicens (01, 04), S. Pérez-Segú (03), A. Martínez-Olalla (02)).

different groups of bees. Examples of these substrates are the so-called “insect hotels” for cavity-nesting bees [37], mounds of earth for ground-nesting bees [38], and straw bales for bumblebees [39]. Cavity-nesting bees also require materials to build the nest, such as mud, the leaves of certain plants or resin.

9.2.5 Reduction of phytosanitary treatments

In addition to floral resources and nesting substrates, pollinator communities require an environment which is as pesticide-free as possible. There is a series of **alternative pest control methods** to chemical control. These methods include firstly the promotion of natural communities of predators and parasitoids (conservation biological control), and also mating disruption involving pheromones, mass capture traps, and the provision of natural enemies bred *ex situ* (flood-inoculation biological control; [40]). Pesticide treatments should only be applied based on an **assessment of exposure thresholds** and/or of favourable environmental conditions for the pest or disease, and considering the possible presence of natural enemies. Whenever treatment is necessary, products with low toxicity to bees can be chosen [41]. It is equally important to minimise the risk of exposure by pollinators. This involves following the instructions on the label, using appropriate application machinery in correct working order, and preventing the product from drifting to the accompanying flora [42]. In pre-bloom treatments, it is extremely important for them to be applied before the first flowers open. Similarly, post-bloom or petal fall treatments should be applied only when there are no flower left in the field. Integrated production and ecological production are two approaches to reducing pesticides.

9.2.6 Integrated Production

Integrated production (IP), sometimes also known as **integrated pest management** (IPM), is a concept that first arose in the 1970s and has been regulated since the 1990s thanks to the **International Organisation for Biological Control (IOBC: https://www.iobc-global.org/)**. It is defined as an agricultural food production system which prioritises the use of naturally regulated resources and mechanisms in order to optimise production methods, avoiding contributions which are harmful to the environment and ensuring sustainable long-term agriculture and livestock breeding [43]. IP focuses on preventing pest infestations and diseases, and is based on the principle of “treating only when strictly necessary”, provided the economic viability of farms is ensured. With this idea in mind, IP monitors pest levels and sets thresholds to help decide whether or not an application is required.

The decision to use a pesticide is only made when other non-chemical control methods have been exhausted. Furthermore, IP promotes other sustainable agricultural practices, such as maintaining plant cover, establishing insect shelters, and promoting food resources for natural enemies and pollinators [44].

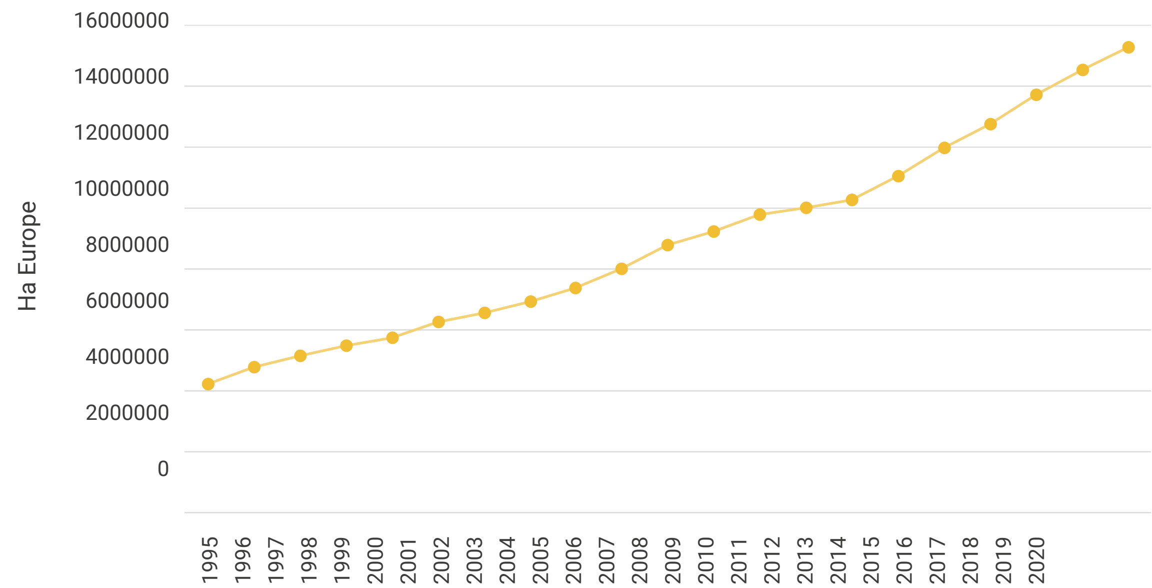
IP is an important part of EU policy regarding plant protection products. The European Union established that all Member States had to include an action plan for integrated pest management by 2014. In Catalonia, IP has been implemented since 1992, and initial regulations were published in 1995. The total area of agricultural land used for IP doubled in Catalonia between 2007 and 2015 to reach 50,750 ha (8% of all agricultural land). Over recent years, the total area of IP has remained at around 6.5% of all agricultural land (excluding forage), in relation to 86% conventional management and 7.5% organic management [45]. IP is extremely relevant in the sweet fruit sector, where it accounts for 32% of the total cultivated area, regarding 64% conventional production and 4% organic production [45].

9.2.7 Organic farming

The goal of **organic farming** (also known as **biological or ecological farming**) is to obtain top quality food and respect the health of ecosystems. Organic farming became popular in Europe in the 1980s, following awareness of the negative effects of agricultural intensification, and has not stopped growing since.

Organic farming is based on the use of production techniques which respect the natural cycles, promote biodiversity, and offer a drastic reduction in resources outside the farm. The use of plant material that is not overly sensitive or resistant to pests and diseases, the promoting of biological control for conservation, and

EVOLUTION OF TOTAL AREA USED FOR ORGANIC FARMING IN EUROPE (2000–2020)



EVOLUTION OF TOTAL AREA USED FOR ORGANIC FARMING IN CATALONIA (1995–2020)

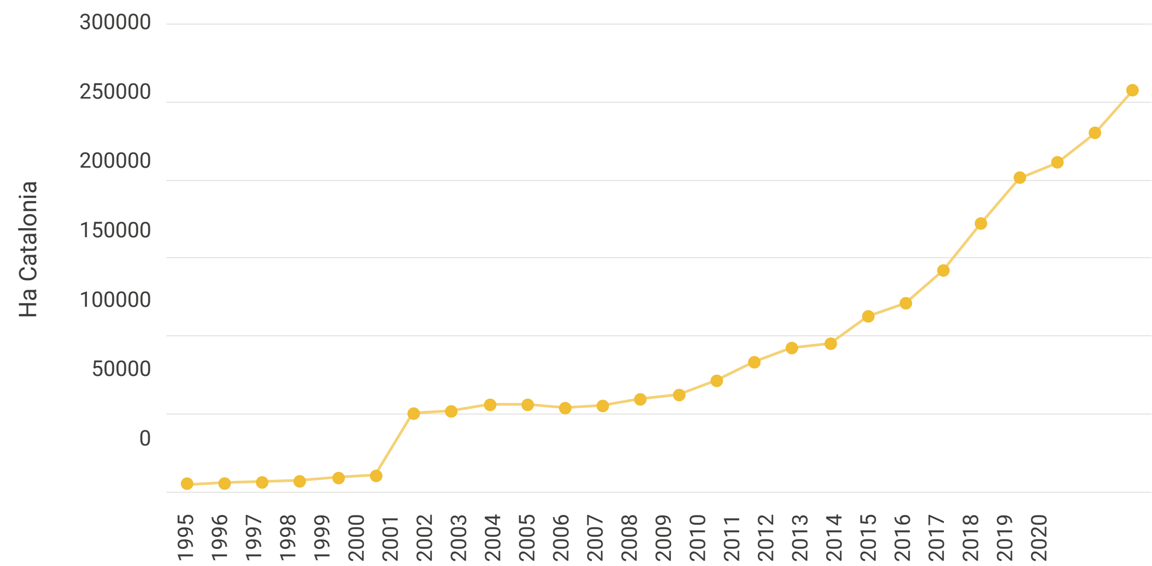


Fig. 23. Total area of organic farming in Europe and in Catalonia over recent decades. (Source: [55])

the implementation of practices that decrease the impact of pests and diseases and use natural resources responsibly are all key to meeting the goals of organic farming.

Some of the practices used in organic farming (biological pest control, crop rotation, mating disruption for pest control, and others) are also used in integrated production, although only pests accepted by European organic production regulations can be used in organic farming. Another significant difference to integrated production is that organic farming places a ban on the use of genetically modified herbicides and organisms.

Organic farming encourages the implementation of permanent plant covers and the maintaining of margins and hedgerows. Numerous studies show that organic management has a positive impact on insect communities in general [36,46] and on pollinators in particular [47–50]. Other studies show that pollinator diversity in organic fields ensures similar pollination services and production to those obtained in integrated production [50,51].

A common regulation defining Organic Production of Agricultural Products has been in place in the European Union since the year 1991 (EEC 2092/91). The total area of organic management has grown considerably in Europe since the early 90s (Fig. 23). In Catalonia, the **Catalan Council of the Organic Production (CCPAE)** is the body responsible for regulating organic production [52]. The total area of organic crops in Catalonia has doubled over recent years (Fig. 23) to reach 257,000 in 2020 (22.1% of all agricultural land, including forage) [53]. The crops to have most increased the total area of organic management over recent years are the vine (27161 ha), followed by fruit trees (1749 ha) and pastures, meadows and forage (183077 ha) [54].

9.2.8 Other models of sustainable agricultural production

In addition to integrated production and organic farming, there are other models of sustainable agriculture which include a **holistic view of agricultural systems** and which are increasingly widespread. These models include **biodynamic agriculture**, **regenerative agriculture** and **permaculture**, although the latter two are not certified.

As part of the new Sustainable agriculture Law, headed by the Ministry of Climate Action, Food and Rural Agenda (DACC), **Sustainable Agricultural Production** (PAS) is considered a new production model to objectively and quantitatively assess, classify and recognise Catalan farms according to their level of sustainability from an environmental, social and economic viewpoint [56]. This new model strives to foster more sustainable agricultural practices based on the principles of agroecology. PAS is intended to make food production compatible with the conservation of resources, preservation of the environment (air, water, biodiversity, land, materials and energy), and social and economic milestones.

PAS also seeks to help mitigate climate change and adapt to its impacts, reversing the loss of biodiversity. The goal for 2030 is for a large number of farms in Catalonia to be part of this new sustainable production. PAS is an inclusive model, with space for organic farming and incorporating IP practices, which may be supplemented to achieve the three pillars of sustainability (economic, social and environmental) [56]. This new model plans to be a certified system for public, voluntary classification as a way of differentiating the products from these farms. From an environmental viewpoint, data from the farms is to be monitored to calculate environmental footprints [56].

9.3 PRACTICES TO BENEFIT POLLINATORS IN URBAN ENVIRONMENTS AND ROAD STRUCTURES

As explained in Section 3.3, the correct management of **public green spaces** and private **gardens and vegetable plots** in urban and semi-urban areas can transform these areas into favourable habitats for some pollinator groups. It is therefore important to increase the area occupied by green spaces while establishing connected corridors between them and with any natural and semi-natural areas on the outskirts of the urban centre [57]. Within the urban grid, the landscaping of avenues and roads is a good measure in establishing connections between green spaces. On a peri-urban level, restoring and replanting the verges of **roadway infrastructures** also encourages pollinator populations, not only in peri-urban areas but also in dense, continuous areas of forest [58]. Roadway infrastructures can also act as connectors between different areas of nature. In Catalonia, a network of green corridors would be of particular interest to connect the countryside areas of the littoral and pre-littoral mountain ranges in such a highly developed area as the El Vallès plain.

The design and management of green infrastructure is essential in ensuring it is effective in promoting pollinators and other groups of fauna. Locally native plants species must first be used, including grass, shrub and tree species of different botanical families, wherever possible. This diversity of flora will encourage the diversity of pollinators. Equally important is the combining of species which flower at different times of the year and which, as a whole, ensure a continuity of floral resources throughout the period of pollinator activity. To encourage pollinators, it is important to choose plants which product large quantities of pollen and nectar [59], and foodplants for butterfly larval stages [60]. Lists of native plants which are attractive to wild bees in different bioclimatic zones of Catalonia can be consulted on the website of the Government of Catalonia's Environment Ministry [59]. The Museum of Natural Science in Granollers has published a practical manual for the creation of gardens that encourage butterflies, with lists of species which act as a source of nectar for adults and as foodplants for caterpillars [61]. Creating these favourable habitats for pollinators is only useful if treatments with plant protection products is reduced to a minimum. The use of these products in gardening is less justified than in agriculture, and there are different initiatives in place in Catalonia, both through the authorities and through gardening associations, to eliminate their use in the management of parks and gardens.

Fig. 24. An insect hotel in a park in the city of Barcelona. (Photograph: P. Bosch).

All these measures must be accompanied by a **management plan** designed for each green space. A good measure to encourage pollinators is the proliferation of grassland at the expense of "lawn" areas. Whenever lawn areas require maintenance, they can be combined with other types of plant life in spaces which are less frequented by users and in areas of difficult access, such as slopes. The rationalising of cutting programmes, especially outside the fire risk period, is also an important measure in encouraging pollinators. For example, in spaces where frequent cutting is required, certain spots containing flowers could be left for the continuity of floral resources. Similarly, alternating sections of the verges of transport infrastructures could be cut to ensure flowering throughout the year [62]. Of course, this cutting schedule must respect driving visibility and safety and fire prevention criteria.

In addition to providing food for pollinators, urban spaces could house nesting sites for bees and wasps, such as areas of bare land for ground-nesting species and nesting stations for cavity-nesting species. Bees and wasps which nest in these structures are not aggressive and, therefore, are of no risk to users. Several urban parks and gardens in Catalonia have insect hotels (Fig. 24) which, apart from providing nesting facilities for solitary bees and wasps, are a significant educational resource to raise awareness of the importance of pollinators.

9.4 MEASURES TO IMPROVE THE TRACEABILITY OF PESTICIDES

The report produced by the **European Court of Auditors** to assess whether the European Union is meeting the objectives of reducing the use of plant protection products [63], underlines the need for increased **traceability of the use of pesticides.** This involves improving the information recorded on the products, doses, application methods, dates and crops, so that the estimated use of products is not based solely on data regarding tonnes of product sold [64]. Plant protection product packaging includes a registration number and a batch number to ensure it is traceable from the point of sale to the purchaser. Despite this, recording the batch number in farming logbooks is not mandatory, which makes it difficult to monitor when or where the product is used. Pesticides for professional use can only be sold in Catalonia to those holding a licence for plant protection product applicators and handlers. Large estates must consult with an appropriately trained professional before applying pesticides, although farms considered small or using few plant protection products (such as many dry land farms) are exempt. The product may only be applied by someone who, after a period of training, has obtained the licence for plant protection product applicators and handlers. Applicators of plant protection products must record the phytosanitary treatments used in a **farming logbook** which must be validated by a qualified expert accredited by the Ministry of Climate Action, Food and Rural Agenda. Farming logbooks and the purchasing records of products are subject to random **inspections** by this Ministry. These inspections guarantee that only authorised products are used in the adequate doses and at the appropriate times, and to ensure the residue levels of the end product are suitable for consumption. The inspections are particularly strict and frequent on farms requesting organic production certification or other quality certifications, although this type of management, in theory, uses fewer pesticides and/or less toxic products.

Although the area involved is much smaller, pesticides are also used in small vegetable plots and private gardens. Some plant protection products can be purchased privately in small quantities in gardening shops, agricultural material warehouses and ecommerce platforms without any kind of certification. In this case, no consulting is necessary and there is no legal obligation to obtain certification to apply the products. Some municipalities in Catalonia restrict the use of pesticides in urban vegetable plots.

9.5 REGULATION OF THE IMPORTING AND MOVEMENT OF POLLINATORS

The introduction of exotic pollinators involves a series of risks, such as possible competition with native pollinators and the introduction of associated parasites and pathogens. Over recent decades, the **introduction of exotic insects** associated to **international trade** has increased alarmingly. It is extremely important, therefore, to correctly control the quarantine and sanitation measures of imported goods that could contain exotic species.

Exotic species, however, can also be introduced intentionally. In today's globalised world, obtaining any type of products is increasingly easy, including live insects from other countries. In Spain, the importing of exotic pollinator species and, in fact, of any foreign animal is forbidden. Authorisations can be obtained, however, if it can be sufficiently guaranteed that the introduction will not have a negative impact on the conservation of native biodiversity. These authorisations can only be obtained following the submission of a report by the applicant to show that the species is not likely to compete with native species or alter their purity or the balance of nature [65,66].

The risks associated to the movement of pollinators, however, is not limited to the introduction of exotic species. Some native species of managed pollinators, such as the honey bee and bumblebees (*Bombus terrestris*), can be legally imported from other countries. Along these lines, the international trade of beekeeping material, queen honey bees and inhabited hives is permitted, although this has recently been suspended as a precautionary measure during certain periods for health reasons. The importing of bumblebees from other countries is also permitted. This species is registered as a commercial product for use in agriculture, as is the case of some insects and mites which are commercialised as natural enemies of pests, provided they are native species. As indicted, these imports can affect the genetic composition of native populations and act as an inway for unwanted parasites and pathogens.

9.6 PROMOTIONAL, AWARENESS-RAISING AND DISSEMINATION MEASURES

It is important to generate **technical guidelines** and **best practices** in line with the conservation of pollinators for each sector and agent in the territory involved in the conservation of wild pollinators. The crucial role must therefore be highlighted of the agricultural sector, of plant production product manufacturing and distribution companies, of the municipal authorities and other local bodies, of environmental and conservationist entities and of other civic organisations representing civil society. Support for the initiatives implemented by these sectors through grants, financial incentives, measures to promote, advise on and improve the visibility of the projects they uphold can significantly help conserve pollinator habitats on different territorial scales.

Along these lines, **informative and awareness campaigns and programmes** can be promoted, aimed specifically at different groups, on the ecological, economic and human health and well-being related importance of pollinators and the promotion of best practices for their conservation. The raising of social awareness on the effects of pesticides on bees has increased greatly over recent years. Despite this, the perception of risk is often restricted to the mass intoxications causing high mortality rates in honey bee hives. Greater awareness is yet to be raised on the sublethal effects and the wide diversity of pollinators which could be affected. To improve this situation, informative campaigns aimed at professional farmers and private individuals could have a great impact.

Initiatives for the coordinated improvement of knowledge about pollinators and their distribution and monitoring are also necessary through mechanisms involving the population, such as citizen science.

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EXECUTIVE SUMMARY

DIAGNOSIS, AREAS OF ACTION AND MEASURES FOR CONSERVATION

Eupeodes corollae (Diptera, Syrphidae) on the flower of a dog rose, *Rosa canina.* (Photograph: N. Vicens).

EXECUTIVE SUMMARY
PART ONE: DIAGNOSIS

1. THE IMPORTANCE OF POLLINATION AND OF POLLINATORS

Pollination as a key process in the functioning of natural ecosystems

Pollination consists of grains of pollen being transferred from the anthers of a flower (male part) to a stigma (female part). It is a prior, necessary process for the sexual reproduction of many plants and an essential ecological process for the functioning of ecosystems. Almost 90% of all flowering wild plants depend to some extent on pollinators (primarily insects) for fruit and seed formation. A generalised pollinator decline, therefore, would affect not only the reproduction of many plants but also the survival of many animals which feed on fruit and seeds and, in short, the stability of the entire trophic network.

Pollination as a ecosystem service

Pollinators provide us with an essential ecosystem service in the form of crop pollination. 75% of all cultivated plants worldwide depend on pollinators to produce fruit and seeds. These include melons, watermelons, pumpkins, kiwis, cocoa and some almond varieties, with an extremely high degree of dependence (90–100%). Other crops which depend on pollinators include a great many fruit trees (apple, pear, cherry), cucumbers, mangoes or avocados (40–90% dependence), and many vegetable and fruit plants such as aubergines, peas, beans, peppers and strawberries and some oilseed plants such as rapeseed and sunflower (10–40%). In Catalonia, over 100,000 hectares of cropland depend, at least partly, on insect pollination.

Insect pollinators

The diversity of insects which visit flowers to feed on pollen and/or nectar is extremely high. Most are Coleoptera (around 750 species of flower-visiting beetles in the Iberian Peninsula), Lepidoptera (230 diurnal and many nocturnal butterflies), Diptera (particularly Syrphids and Bombyliidae, 400 and 200 species, respectively; although many others) and Hymenoptera (ants, wasps and bees). Bees (1100 species in the Iberian Peninsula) collect nectar and pollen not only for their own consumption but also to feed their larvae, which is why they visit a great many flowers. Some bee species, such as the honey bee and the bumblebee are social, although most (90%) are solitary. Most bee species dig nests underground. The diversity of bees is particularly high in Mediterranean climate zones.

Pollination effectiveness

Pollination effectiveness (defined as the number of grains of pollen transferred per floral visit) varies greatly and depends not only on the pollinator species but also on the plant species. For most plants, bees are the most effective pollinators which contribution most to pollination. The quality of the pollen transferred is also important. Pollinators visiting a lot of flowers of the same plant favour self-pollination and, therefore autogamy. Pollinators visiting a few flowers per plant and flying long distances between plants favour exogamy and gene flow and, therefore, genetic diversity.

Plant-pollinator interaction networks

There are often dozens of plant species and hundreds of pollinator species in a plant community. Some pollinator species only visit one or a few plant species, although most behave as generalist species and visit a wide variety. The relationship between pollinators and plants forms complex interaction networks. In the undergrowth of El Garraf Nature Reserve, a pollinator species visits an average of 4–5 plant species, and a plant species receives visits from an average of 30–40 pollinator species. This high level of connectivity means that a disruption, such as the extinction of a certain species or the introduction of a new one, might affect the community as a whole.

The importance of diversity

Pollinator diversity is essential in guaranteeing the functioning of ecosystems. Communities with a high functional diversity of pollinators are more resilient to natural and anthropogenic disturbances. Diverse communities have a high degree of complementarity (species with different functions) which means that all the plants receive a good pollination service. Complementarity also becomes apparent when different pollinator species visit the same plant under different circumstances (in different weather conditions, for example). Diverse communities also have a high degree of redundancy (species with similar functions). This redundancy means that, if a species becomes extremely scarce or disappears, others are able to maintain the pollination service.

2. STATUS AND TRENDS OF POLLINATOR COMMUNITIES AND POPULATIONS

Pollinator declines worldwide

Over the past century, extremely significant declines have been detected in the diversity and abundance of insect pollinators, particularly bees and butterflies. These declines have been documented in countries in northern Europe and America, where there are good historic records of communities of insect pollinators. A study in Germany indicates 70% losses in flying insect biomass over the past 25 years. It is important to note that the declines do not affect all species equally. In the case of bees, large-sized species, those with a long proboscis, and those with a high degree of specialisation in terms of habitat and diet are most affected. This different impact leads to a depletion in functional diversity and a biotic homogenisation which endangers the pollination service throughout the community.

Butterfly declines in Catalonia

Thanks to monitoring over the past three decades by the CBMS (Catalan Butterfly Monitoring Scheme), high quality information is available on the population trends of diurnal butterflies. CBMS records show declines of around 70% in the species in Catalonia. Similar to bees, butterflies behaving as habitat or diet specialists are those to have undergone the most significant declines. For example, butterflies associated to meadows and grasslands have declined much more than those preferring forest environments. The CBMS also detected that 5% of monitored butterfly populations in Catalonia have become locally extinct.

Threatened species

Of the 2000-plus species of bees in Europe, 9% are considered threatened and 37% are in decline. The group of bumblebees is particularly noteworthy, with 26% of threatened species. It is also important to note that insufficient information is available for 57% of all bee species, particularly in the Mediterranean area. In the case of diurnal butterflies, the European red list estimates that 9% are threatened and 31% are in decline. Based on CBMS data, the Catalogue of Threatened Native Wild Fauna of Catalonia includes 45 species of diurnal butterflies, of which 12 are "endangered", 32 are "vulnerable" and one is "extinct for reproduction in Catalonia", which means 22% are threatened species. Apart from butterflies, there is not population data on other pollinator groups in Catalonia.

Honey bee population trends

Despite the growing difficulties experienced by the beekeeping sector due to climate change, the arrival of new natural enemies and the commercial competition from major honey producing countries, honey bee (*Apis mellifera*) populations are not in decline in Spain or in Catalonia. In Catalonia, the number of hives has risen from 46,500 in 1996 to 122,000 in 2020. The majority of Catalan beekeeping operations (78%) are nomadic and deal in honey production (71%) or combine honey production with crop pollination (23%).

Managed pollinators

The honey bee is by far the managed pollinator most used around the world in the vast majority of crops. In light of the risk of depending on one single species, breeding and management methods of other bee species have been developed for certain crops. In North America, commercial populations of a leafcutting bee (*Megachile rotundata*) are used to pollinate alfalfa. Colonies of bumblebees (*Bombus* spp.) are used in different parts of the world to pollinate greenhouse crops and, more recently, outdoor crops. The use of populations of solitary bees of the genus *Osmia* to pollinate almond and other fruit trees is growing in eastern Asia, North America, and Europe.

Exotic pollinators

Given the rise in inter-continental trade, the inadvertent introduction of insects has grown at an alarming rate over recent decades. The arrival of exotic (or foreign) species of both animals and plants could have an extremely significant ecological and economic impact. These species could compete with native species and promote the arrival of new parasites and diseases. Exotic pollinator species in Catalonia include the giant resin bee (*Megachile sculpturalis*), the Asian hornet (*Vespa velutina*) and various butterflies and solitary wasps.

3. CAUSES OF POLLINATOR DECLINE

Overview

There are many different causes of insect pollinator decline, including changes in land use (agricultural intensification, urban development, habitat fragmentation, loss of open spaces) and climate change. It is important to note that these factors can act simultaneously and produce not only cumulative but also synergistic effects. Nutritional stress, for example, which makes pollinators more vulnerable to disease or to pesticides. Calculating the impact of each factor is, therefore, a difficult task.

Agricultural intensification

Agricultural intensification involves a more intensive use of the land and is based on a series of practices such as the use of heavy machinery, an increase in the size of cropland plots, the trend towards monoculture, and the use of chemical fertilisers and pesticides. This process brings with it the destruction of the margins of fields and the disappearance of fallow land, waste land, and semi-natural habitats, thus decreasing the abundance and continuity of floral resources and altering the nesting substrates of bees. It also involves an increase in the environmental load of toxic products. Agricultural intensification is probably one of the factors to have most contributed to pollinator decline. Given its importance and complexity, the subject of plant protection products is discussed in a separate chapter (Chapter 4).

Genetically modified (GM) crops

The only GM crop permitted in the European Union is modified corn to express the Cry1Ab toxin and produce an insecticidal effect. In Catalonia, around 27,000 ha of corn is cultivated, 50% of which is GM. In initial studies conducted in the United States, the pollen of GM corn was considered a danger to monarch butterflies. However, different studies have shown that the levels of inadvertently ingested GM pollen by caterpillars are negligible. Nor were major effects of GM pollen on bees found in laboratory and field studies. Herbicide-resistant GM crops (not authorised in the European Union) favour the use of these products to control so-called "weeds" and, therefore, could have an indirect, negative effect on pollinators due to the reduction in floral resources and foodplants.

Urban development

Urban development represents a radical transformation of the landscape, with a clear impact on the resources and nesting habitats of many pollinators. Hence, urban centres with appropriately managed green spaces are also able to provide certain characteristics favourable to pollinators, such as a great diversity of flowers, a limited use of pesticides, and the availability of artificial nesting substrates. Some studies have found richer pollinator communities in peri-urban areas than in adjacent areas of agriculture or countryside.

Pollution

There are few studies of the impact of pollution on pollinators. Some works indicate negative effects from heavy metals and other contaminants which could come into contact with pollinators through the air, water or soil. Contaminants can also indirectly affect pollinators through their effect on plant life.

Afforestation

Communities of pollinators are richer and more abundant in open environments than in dense forest areas in which the undergrowth receives little light and there are few flowering plants. Over recent decades, the Mediterranean basin in general and Catalonia in particular have experienced a process of abandonment of traditional, low intensity agricultural-livestock farms, leading to the spread of forest land and the eradication of clearings, meadows and grassland. This is resulting in a decreased diversity of butterflies and bees in forest environments in Catalonia.

Habitat fragmentation

As a result of the aforementioned changes in land use, favourable habitats for pollinators have become fragmented. Fragmentation leads not only to the decrease but also to the isolation of favourable habitats, which become a group of disconnected spots. Fragmentation reduces the abundance and diversity of pollinators, with consequences on the pollination levels and reproductive success of plants. Furthermore, it can hinder the gene flow between populations.

Climate change

Climate change can affect pollinators directly, for example by increasing energy expenditure during warm winters or by modifying development rates and life cycles. Some pollinator species are changing their flight period, which tends to be brought forwards. These phenological changes can result in time-based imbalances with key events such as the arrival of winter, flowering or the available of food resources for larvae. Climate change is also affecting the distribution areas of many pollinators, which are moving latitundally and altitudinally towards areas that are historically colder. Climate change can also indirectly affect pollinators through its effects on plants. High temperatures and drought, for example, can alter flower production and nectar secretion, and also have a negative effect on the foodplants of many caterpillars.

Biological invasions

The inadvertent or intentional introduction of exotic species involves a series of environmental and socioeconomic risks. In the case of pollinators, invasive species could compete with native species for food and nesting resources. Furthermore, invasive species can be vectors of exotic parasites or pathogens, which could infect native species. In the late 1990s, the introduction of commercial populations of the European bumblebee *Bombus terrestris* was introduced into Chile to pollinate greenhouse crops. It has spread rapidly since its arrival, while native bumblebee populations have declined alarmingly. Beekeeping has been affected extremely negatively by the introduction of exotic predators, parasites and pathogens, such as the mite *Varroa destructor*, the fungus *Nosema ceranae*, and the Asian hornet, *Vespa velutina*. Some exotic plants can become important sources of nectar and pollen for pollinators, although they can also become invasive and cause significant changes in the structure of plant-pollinators networks.

Managed pollinators

The introduction of populations of managed native pollinators in crop fields contributes towards agricultural production and to food stability, although it can also involve certain risks to wild pollinators. Managed pollinators could be a source of pathogens and parasites which can infect local populations of wild pollinators. Furthermore, managed pollinators can mate with wild individuals of the same species, thus altering the genetic composition of the wild populations. In the Iberian Peninsula, significant levels of genetic introgression have been recorded in the honey bee and the bumblebee *Bombus terrestris*.

Beekeeping intensification

The honey bee forms large colonies with hundreds of thousands of specimens and, therefore to its recruiting capacity, it exploits flowers very effectively. The installation of significant hive densities in areas of countryside could lead to the over-exploitation of floral resources and result in competition with wild pollinators. Calculating the bee colony carrying capacity in a specific area is a complex task, although different studies indicate that, at current densities, this competition is already occurring in some areas of nature.

4. PLANT PROTECTION PRODUCTS

Plant protection products

The use of pesticides (basically insecticides, fungicides and herbicides) is an essential component of agricultural intensification. Apart from the beneficial effect they might have in controlling certain pests and diseases, pesticides have a series of unwanted effects such as environmental contamination and impact on non-target organisms. Integrated production and ecological production are two approaches to reducing plant protection products. Both strategies have been promoted in the European Union since the 1990s but, despite this, the sale of pesticides has not declined. One of the objectives of the new Common Agricultural Policy, of the Biodiversity Strategy for 2030 and of the *From Farm to Fork* Strategy is a 50% reduction in the use of plant protection products by the year 2030. The use of pesticides should also be decreased in urban environments, where its use is more difficult to justify than on farms.

Exposure pathways and effects of pesticides

Pollinators can be contaminated by pesticides via different exposure pathways, including the ingestion of contaminated pollen and nectar and contact with surfaces to which the treatment has been applied, such as plants or soil. Soil exposure is particularly significant for ground-nesting bees and wasps. Another significant exposure pathway is contact with the dust generated when planting seeds treated with insecticide. The effects of pesticides on pollinators can be lethal or sublethal. Despite being less drastic, sublethal effects alter the activity of the pollinator and its reproductive success, so they can have very negative consequences on the population.

Fungicides and herbicides

Fungicides are not overly toxic to insects and their use during crop bloom is therefore permitted. Despite this, some fungicides can synergistically promote the toxicity of certain insecticides, causing lethal and sublethal effects. Herbicides are also not overly toxic to bees although they can have sublethal effects, such as altering their gut microbiota. Furthermore, herbicides have a significant, indirect effect on pollinators by destroying floral resources and the foodplants of butterfly larvae.

Insecticides

Most insecticides are toxic to bees, and their use is banned during crop bloom. It must be noted, however, that systemic insecticides applied pre-bloom can appear in the pollen and nectar of the treated crops, and that some insecticides have a high degree of persistence in the soil. Insecticides have also been found in wild flowers, probably having drifted from phytosanitary treatments in crops. In view of the accumulated evidence relating neonicotinoids with lethal and sublethal effects in bees, the EU banned the use of different products from this group of insecticides in field treatments in 2018. Restrictions of this type have not been applied, however, in many other countries.

Multiple exposure

Pollinators are often simultaneously exposed to multiple products in agricultural environments. This multiple exposure may be due to applications which mix different products, but also to products applied at different times. Residues from systemic insecticides applied during pre-bloom which appear on the flowers of treated crops can mix with fungicide treatments applied during bloom. Analyses of pollen collected by bees in agricultural environments often contain many different residues of insecticides, acaricides, fungicides and herbicides. Despite being at low concentration levels, the possible effects of this multiple exposure are unknown.

Risk assessment

Risk assessment of plant protection products includes a series of laboratory, semi-field and field toxicity tests with the honey bee. Risk assessment is an essential process in protecting pollinators, and is updated as new assessment methods are refined. Some aspects of risk assessment programmes to improve upon include a wider coverage of chronic exposure, exposure to product mixtures and the detection of sublethal effects. The results obtained with the honey bee, *Apis mellifera*, cannot always be extrapolated to other bee species. Therefore, the European Food Safety Authority (EFSA) recommends including bumblebees (*Bombus terrestris*) and solitary bees (*Osmia* spp.) in risk assessment programmes.

5. CROP POLLINATION IN CATALONIA: DEFICITS AND STRATEGIES

Pollination deficits and crop pollination strategies

Wild pollinator communities contribute very significantly towards crop pollination. In some cases, however, such as in mass-flowering crops in an areas of intensive agriculture, there might be insufficient wild pollinators to provide an adequate pollination service. Faced with a pollination deficit, measures can be taken to promote wild pollinator communities. To this end, it is important to encourage not only the abundance but also the functional diversity of these pollinators. A second strategy of action is the introduction of managed pollinator populations, such as honey bees, bumblebees or osmia. The recommended densities must always be introduced so as not to cause the over-exploitation of floral resources.

Evaluation of insect pollination of crops in Catalonia

Insect pollination is a key ecosystem service for agricultural production in Catalonia. The crops which depend on pollinators include fruit trees (14% of the total cultivated area), such as the almond, cherry, apple and pear. Other crops which depend on pollination include certain legumes (1%) such as the French bean and broad bean, different vegetables and fruits (1%) such as the tomato, melon, watermelon and strawberry, and certain industrial crops (2%) such as rapeseed and sunflower. Forage crops (17%) must also be mentioned, some of which, such as the alfalfa, sainfoin or vetch, are sown using seeds produced by insect pollination. On average, the market price of crops which depend on insect pollination is higher than non-dependent crops. The value of crop pollination by insects in Catalonia stands at around 290–321 million euros per year.

6. IMPROVEMENTS IN KNOWLEDGE OF POLLINATOR DECLINES

This report has identified a series of shortfalls in knowledge on pollinator declines in Catalonia. Firstly, a programme must be established to monitor the pollinator populations and catalogues and distribution maps of the main pollinator groups (bees and syrphids) produced, comparable to those which already exist for butterflies. It is also important to assess the adequacy of the management of protected areas for the conservation of pollinators. Secondly, ascertaining the real impact of phytosanitary treatments on pollinators is essential. This involves increased research in realistic field conditions and establishing a monitoring programme of the residue levels in agricultural environments. A report by the European Court of Auditors highlights the lack of detailed records and statistics on plant protection products, which hinders the strict analysis of data. Thirdly, it is important to review certain aspects of the pesticide risk assessment programmes, with greater coverage of chronic exposure, product mixtures, sublethal effects, and the inclusion of other pollinator species apart from the honey bee. Lastly, methods must be refined to assess the carrying capacity of bee colonies in terms of the landscape to be able to establish hive density thresholds and combine honey production with the conservation of wild pollinators.

PART TWO: PRIORITY AREAS OF ACTION AND MEASURES FOR THE CONSERVATION OF WILD POLLINATORS IN CATALONIA

7. IDENTIFICATION OF PRIORITY AREAS AND OBJECTIVES OF ACTION

Overview

The Natural heritage and biodiversity strategy of Catalonia 2030 foresees the drafting of an Intersectoral plan for the conservation of wild pollinators. The proposed priority areas of action are drafted in accordance with this diagnosis and different national and international strategic reports and instruments, such as the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2016), the EU pollinators initiative (2018), the EU Biodiversity Strategy 2030 (2020), and the National Strategy for the Conservation of Pollinators (2020).

EU Biodiversity Strategy

The new UE Biodiversity Strategy for 2030 sets out a vision for the year 2050 in which all the ecosystems in the world have been restored, are resilient and are adequately protected. Along these lines, the objective for 2030 is to put Europe's biodiversity on the path to recovery for the benefit of people, the planet, climate and the economy. Among the specific commitments and targets regarding the restoring of nature in Europe is the target of reversing pollinator decline. In line with this target, the European Commission will guarantee full implementation of the pollinator initiative in the EU by developing actions to improve knowledge of the causes and consequences of the decrease in pollinators and to address them. The Commission will also focus on raising awareness and mobilising citizens, and on promoting cooperation among all stakeholders.

National Strategy for the Conservation of Pollinators

Within this European framework, the National Strategy for the Conservation of Pollinators sets out six goals: 1) To conserve threatened pollinator species and their habitats; 2) To promote favourable habitats for pollinators; 3) To improve pollinator management and reduce risks from pests, pathogens and invasive species; 4) To reduce the risk of the use of plant protection products for pollinators; 5) To support research to improve knowledge; 6) To guarantee access to information and raise awareness on the importance of pollinators. To meet these goals, the Strategy defines 37 measures to be implemented by 2027.

Priority goals and measures of the Intersectoral plan for the conservation of wild pollinators in Catalonia

In this context, the Intersectoral plan for the conservation of wild pollinators in Catalonia should establish priority goals and measures in the following areas: 1) Improved knowledge: Improve knowledge of the conservation status of wild pollinators and the causes of their decline; 2) Agricultural and food production environment: Increase best practices in the agricultural environment which favour the conservation of wild pollinators; promote favourable habitats for pollinators in the agricultural environment; improve pollinator management and reduce the risks arising from parasites, pathogens and predators; 3) Urban and peri-urban environment: promote favourable habitats for pollinators in the urban environment; include the conservation of pollinators in the management of green spaces and of urban and peri-urban parks; take measures to favour pollination populations in environments associated with transport infrastructures, energy and other services; 4) Reduced use of plant protection products: identify and reduce the harmful effects of plant protection products; reduce the risk arising from plant protection products to pollinators in the agricultural environment and in urban environments and major infrastructures; 5) Beekeeping and wild pollinators: ensure the compatibility of the beekeeping activity with the conservation of wild pollinators; 6) Society and entities: raise awareness of the importance of pollinators; encourage participation in pollinator conservation measures; guarantee access to information on pollinators and pollination.

8. MEASURES AND BEST PRACTICES FOR THE CONSERVATION OF WILD POLLINATORS

Based on the knowledge available both in general and within the context of Catalonia, certain measures may be suggested to meet the goals of the above section.

Practices to benefit pollinators in protected natural environments

32.8% of Catalonia form protected areas of nature, the objective of which is to conserve biodiversity and ensure the use of resources and the activity of their inhabitants are compatible with this objective. This should ensure the conservation of pollinator populations, although there are many examples of species which have recorded a significant decline, even local extinctions, in protected areas. To reverse this situation, active management measures must be implemented to help ensure habitats remain beneficial to pollinators. Other measures to consider in protected areas include restricting the number of visits to areas of particularly vulnerable plant life and regulating the densities of honey bee hives.

Practices to benefit pollinators in agricultural environments

Agriculture takes up 25% of the total area of Catalonia. As opposed to agricultural intensification, a new approach known as ecological intensification has been proposed over the past decade. Ecological intensification is based on the integration of ecosystem services into production systems in order to maintain production levels, increase the resilience of agricultural systems, and minimise the negative impacts of agriculture on the environment. Ecological intensification promotes practices which encourage not only pollination but also other ecosystem services such as biological pest control and soil protection.

These practices initially include a reduction in the use of plant protection products. This reduction involves adopting alternative pest control methods, following the guidelines of different models of agriculture such as Integrated Production, Sustainable Agricultural Production, and Organic Farming. Best practices in the use of plant protection products, respecting the conditions indicated on the label and the phenological studies of the crop, and preventing the product from reaching the accompanying flora are also essential in reducing the impact of plant protection products on pollinators. Other measures include crop diversification and rotation, a reduction in field size, the conservation of multifunctional margins, the promotion of habitats beneficial to fauna and flora, such as waste land and fallow land, and the implementation of plant cover and hedgerows. These measures must be accompanied by a reduced use of herbicides and a schedule for the frequency and seasonality of cutting.

Since the 1990s, the Common Agricultural Policy (CAP) has funded Member States in order to encourage the implementation of this type of agri-environmental measures. The new Common Agricultural Policy, which is to come into force in 2023, highlights climate and environmental aspects through the promotion of agricultural practices which help protect and improve natural resources, the land and genetic diversity, and mitigate climate change. The effectiveness of the agri-environmental measures depends on the context in which they are applied. To this end, it is important to act both locally by influencing the management of fields and their immediate surroundings and in terms of the landscape by preserving natural environments.

Practices to benefit pollinators in urban environments and road structures

The correct management of public green spaces and private gardens and vegetable plots in urban and semi-urban areas can transform these areas into favourable habitats for some pollinator groups. Along these lines, it is important to increase the area occupied by plant life that is beneficial to pollinators, such as grassland, and establish connected corridors between them and with natural areas, through the landscaping of roadway infrastructures, for example. The creation and maintaining of these habitats must be accompanied by rationalised cutting schedules and a reduction in phytosanitary treatments, the use of which is less justified in gardening than in agriculture.

Measures to improve the traceability of pesticides

The report by the European Court of Auditors to assess whether the European Union is meeting the objectives of reducing the use of plant protection products underlines the need for increased traceability of the use of pesticides. This involves improving the information recorded on the products, doses, application methods, dates and crops, so that the estimated use of products is not based solely on data regarding tonnes of product sold. Farming logbooks and the purchasing records of products are subject to random inspections. These inspections guarantee that only authorised products are used in the adequate doses and at the appropriate times, and to ensure the residue levels of the end product are suitable for consumption. The inspections are particularly strict and frequent on farms with an organic production certification or other quality certifications, despite the fact that these use fewer pesticides and/or less toxic products.

Regulation of the importing and movement of pollinators

Over recent decades, the introduction of exotic insects associated to international trade has increased alarmingly. It is extremely important, therefore, to correctly control the quarantine and sanitation measures of imported goods that could contain exotic species. The risks associated to the movement of pollinators is not limited to the introduction of exotic species. Some native species of managed pollinators, such as the honey bee and bumblebees (*Bombus terrestris*), can be legally imported from other countries. These imports facilitate the arrival of parasites and pathogens and alter the genetic composition of local populations.

Promotional, awareness-raising and dissemination measures

It is important to produce technical guidelines and best practices for the different sectors and agents in the territory involved in the conservation of wild pollinators. The crucial role must therefore be highlighted of the agricultural sector, of plant production product manufacturing and distribution companies, of the municipal authorities and other local bodies, of environmental and conservationist entities and of other civic organisations representing civil society. Support for the initiatives implemented by these sectors through grants, financial incentives, measures to promote, advise on and improve the visibility of the projects they uphold can significantly help conserve pollinator habitats on different territorial scales. To meet this goal, informative and awareness campaigns and programmes can be promoted, aimed specifically at different groups, on the ecological and economic importance of wild pollinators and the promotion of best practices for their conservation. Finally, the crucial role that citizen science initiatives may have in documenting the population trends of pollinators must be highlighted.

Field of rapeseed (*Brassica napus*) in the Montseny mountain range. (Photograph: Jose Luis Ordóñez).