POLLINATION SERVICES FOR SUSTAINABLE AGRICULTURE

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POTENTIAL EFFECTS OF CLIMATE CHANGE ON CROP POLLINATION

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POLLINATION SERVICES FOR SUSTAINABLE AGRICULTURE

POTENTIAL EFFECTS OF CLIMATE CHANGE ON CROP POLLINATION

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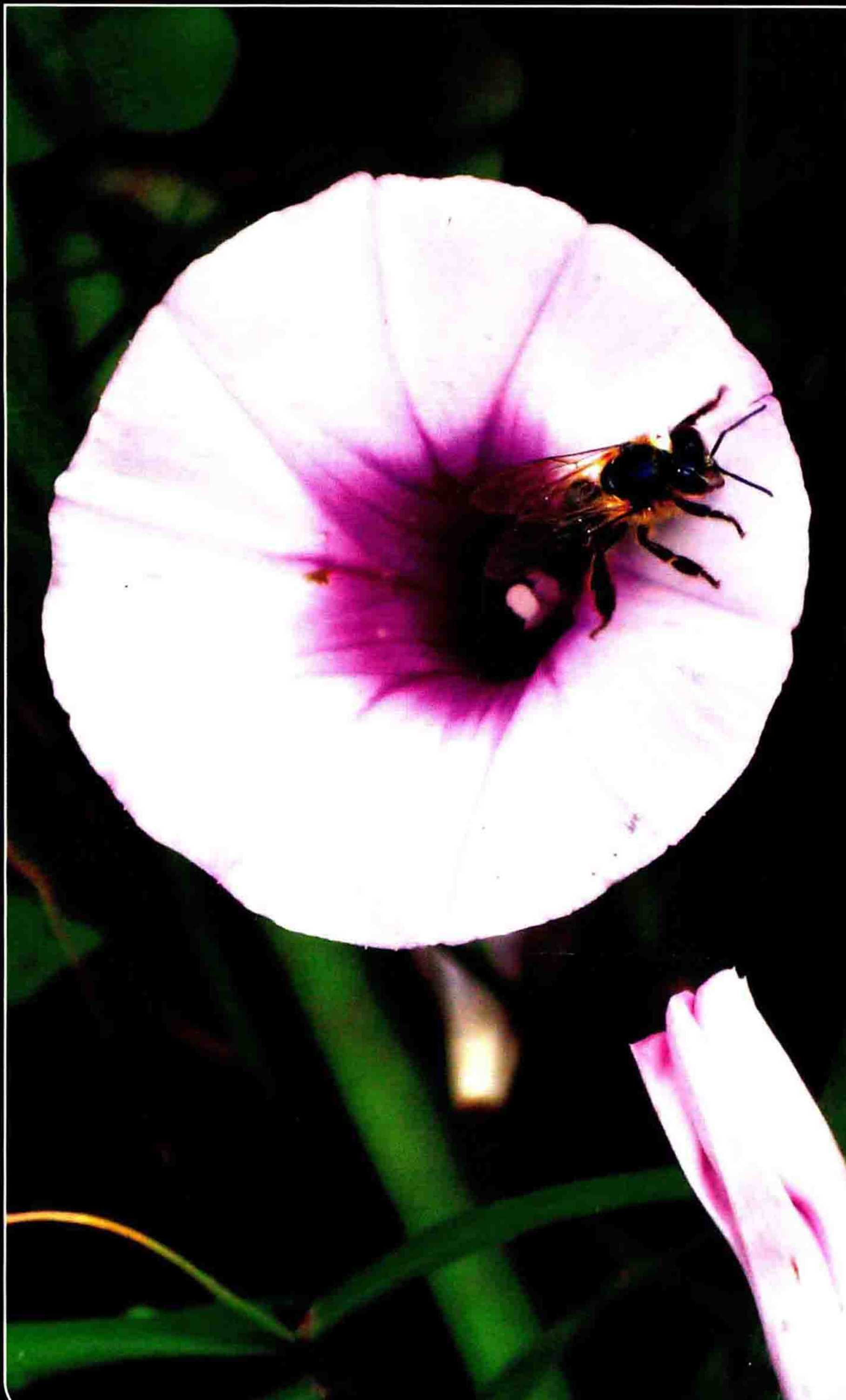

PREFACE

Crop production must meet the demands of feeding a growing population in an increasingly degraded environment amid uncertainties resulting from climate change. There is a pressing need to adapt farming systems to meet these challenges. One of agriculture's greatest assets in meeting them is nature itself: many of the ecosystem services provided by nature – such as nutrient cycling, pest regulation and pollination – directly contribute to agricultural production. The healthy functioning of these ecosystem services ensures the sustainability of agriculture as it intensifies to meet growing demands for food production.

Climate change has the potential to severely impact ecosystem services such as pollination. As with any change, both challenges and opportunities can be expected. Recognizing that the interactions between climate, crops and biodiversity are complex and not always well understood, the Plant Production and Protection Division of FAO has coordinated this review of the potential effects of climate change on crop pollination. By taking a comprehensive, ecosystem approach to crop production, it may be possible to build in greater resilience in farming systems, and to identify broader options for crop production intensification through the deliberate management of biodiversity and ecosystem services.

Within the context of its lead role in the implementation of the International Initiative for the Conservation and Sustainable Use of Pollinators, also known as the International Pollinators Initiative (IPI) of the United Nations Convention on Biological Diversity, established in 2000 (Conference of Parties decision V/5, section II), FAO has developed a Global Action on Pollination Services for Sustainable Agriculture. This report serves as a contribution by FAO's Global Action on Pollination Services to the objectives of the IPI, specifically its first objective to "Monitor pollinator decline, its causes and its impact on pollination services".

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INTRODUCTION
Objectives of the report

One of the most important ecosystem services for sustainable crop production is the mutualistic interaction between plants and animals: pollination. The international community has acknowledged the importance of a diversity of insect pollinators to support the increased demand for food brought about by predicted population increases. Insect pollination is threatened by several environmental and anthropogenic factors, and concern has been raised over a looming potential pollination crisis.

The Intergovernmental Panel on Climate Change (IPCC) reports an approximate temperature increase ranging from 1.1-6.4°C by the end of this century. Climate change will exert great impacts on global ecosystems. A recent review has emphasized that plant-pollinator interactions can be affected by changes in climatic conditions in subtle ways. Data on the impacts of climate change on crop pollination is still limited, and no investigation has yet addressed this issue. This report aims to:

- provide a review of the literature on crop pollination, with a focus on the effects of climate change on pollinators important for global crop production;
- present an overview of available data on the temperature sensitivity of crop pollinators and entomophilous crops; and
- identify data needs and sampling techniques to answer questions related to effects of climate change on pollination, and make recommendations on the recording and management of pollinator interactions data. This includes important environmental variables that could be included in observational records in order to enhance the knowledge base on crop pollination and climate change.

CONTENTS

CLIMATE CHANGE AND CROP POLLINATION

Pollination is a crucial stage in the reproduction of most flowering plants, and pollinating animals are essential for transferring genes within and among populations of wild plant species (Kearns *et al.* 1998). Although the scientific literature has mainly focused on pollination limitations in wild plants, in recent years there has been an increasing recognition of the importance of animal pollination in food production. Klein *et al.* (2007) found that fruit, vegetable or seed production from 87 of the world's leading food crops depend upon animal pollination, representing 35 percent of global food production. Roubik (1995) provided a detailed list for 1 330 tropical plant species, showing that for approximately 70 percent of tropical crops, at least one variety is improved by animal pollination. Losey and Vaughan (2006) also emphasized that flower-visiting insects provide an important ecosystem function to global crop production through their pollination services.

The total economic value of crop pollination worldwide has been estimated at €153 billion annually (Gallai *et al.* 2009). The leading pollinator-dependent crops are vegetables and fruits, representing about €50 billion each, followed by edible oil crops, stimulants (coffee, cocoa, etc.), nuts and spices (Table 1). The area covered by pollinator-dependent crops has increased by more than 300 percent during the past 50 years (Aizen *et al.* 2008; Aizen and Harder 2009) (Figure 1.1). A rapidly increasing human population will reduce the amount of natural habitats through an increasing demand for food-producing areas, urbanization and other land-use practices, putting pressure on the ecosystem service delivered by wild pollinators. At the same time, the demand for pollination in agricultural production will increase in order to sustain food production.

Table 1

ECONOMIC IMPACTS OF INSECT POLLINATION OF THE WORLD AGRICULTURAL PRODUCTION USED DIRECTLY FOR HUMAN FOOD AND LISTED BY THE MAIN CATEGORIES RANKED BY THEIR RATE OF VULNERABILITY TO POLLINATOR LOSS

CROP CATEGORY	AVERAGE VALUE OF A PRODUCTION UNIT	TOTAL PRODUCTION ECONOMIC VALUE (EV)	INSECT POLLINATION ECONOMIC VALUE (IPEV)	RATE OF VULNERABILITY (IPEV/EV)
	€ PER METRIC TONNE	10^9€	10^9€	%
Stimulant crops	1 225	19	7.0	39.0
Nuts	1 269	13	4.2	31.0
Fruits	452	219	50.6	23.1
Edible oil crops	385	240	39.0	16.3
Vegetables	468	418	50.9	12.2
Pulse	515	24	1.0	4.3
Spices	1 003	7	0.2	2.7
Cereals	139	312	0.0	0.0
Sugar crops	177	268	0.0	0.0
Roots and tubers	137	98	0.0	0.0
All categories		1 618	152.9	9.5

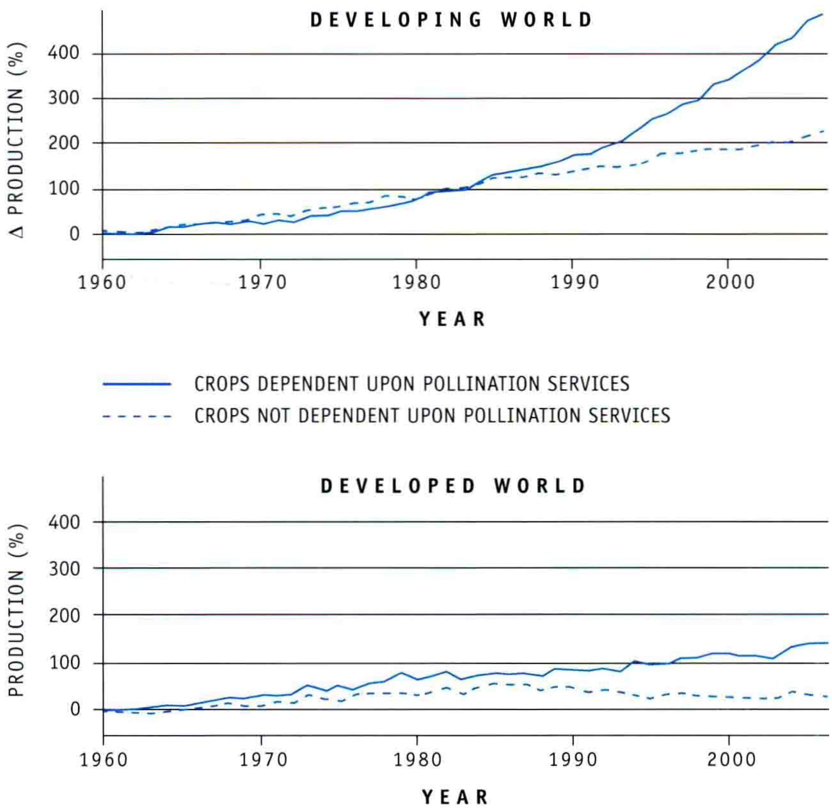
Source: Gallai *et al.* 2009.

Animal pollination of both wild and cultivated plant species is under threat as a result of multiple environmental pressures acting in concert (Schweiger *et al.* 2010). Invasive species (Memmott and Waser 2002; Bjerknes *et al.* 2007), pesticide use (Kearns *et al.* 1998; Kremen *et al.* 2002), land-use changes such as habitat fragmentation (Steffan-Dewenter and Tscharntke 1999; Mustajarvi *et al.* 2001; Aguilar *et al.* 2006) and agricultural intensification (Tscharntke *et al.* 2005; Ricketts *et al.* 2008) have all been shown to negatively affect plant-pollinator interactions.

Climate change may be a further threat to pollination services (Memmott *et al.* 2007; Schweiger *et al.* 2010; Hegland *et al.* 2009). Indeed, several authors (van der Putten *et al.* 2004; Sutherst *et al.* 2007) have argued that including species interactions when analysing the ecological effects of climate change is of utmost importance. Empirical studies explicitly focusing on the effects of climate change on wild plant-pollinator interactions are scarce and those on crop pollination practically non-existent. Our approach has therefore been to indirectly assess the potential effects of climate change

Figure 1.1

TEMPORAL TRENDS IN TOTAL CROP PRODUCTION FROM 1961 TO 2006



Source: Aizen *et al.* 2008.

on crop pollination through studies on related topics. We have focused on the effects of climate change on crop plants and their wild and managed pollinators, and studies on wild plant-pollinator systems that may have relevance.

The Fourth Assessment Report (AR4) developed by the Intergovernmental Panel on Climate Change (IPCC) lists many observed changes of the global climate. Most notably, the IPCC has documented increased global temperatures, a decrease in snow and ice cover, and changed frequency and intensity of precipitation (IPCC 2007). The most plausible and, in our opinion with respect to plant-pollinator interactions, the most important effect of climate change is an increase in temperatures. Therefore, we focus on the impacts increased temperatures might have on pollinator interactions. The fact that 11 years - out of the 12 year period from 1995 to 2006 - rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850) (IPCC 2007) provides high confidence of recent warming, which is strongly affecting terrestrial ecosystems. This includes changes such as earlier timing of spring events and poleward and upward shifts in distributional ranges of plant and animal species (IPCC 2007; Feehan *et al.* 2009).

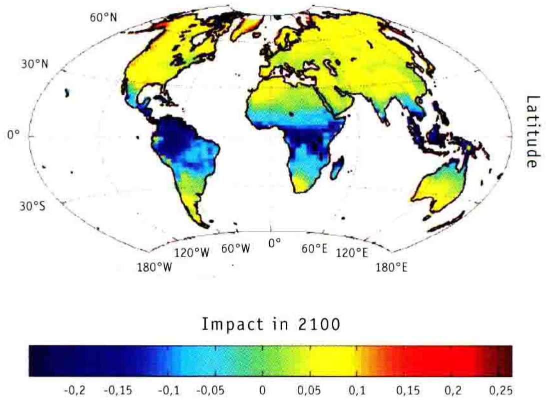
The most plausible and important effect of climate change on plant-pollinator interactions can be expected to result from an increase in temperatures.

Estimates from the IPCC indicate that average global surface temperatures will further increase by between 1.1°C (low emission scenario) and 6.4 °C (high emission scenario) during the 21st century, and that the increases in temperature will be greatest at higher latitudes (IPCC 2007). The biological impacts of rising temperatures depend upon the physiological sensitivity of organisms to temperature change. Deutsch *et al.* (2008) found that an expected future temperature increase in the tropics, although relatively small in magnitude, is likely to have more deleterious consequences than changes at higher latitudes (Figure 1.2). The reason for this is that tropical insects are relatively sensitive to temperature changes (with a narrow span of suitable temperature) and that they are currently living in an environment very close to their optimal temperature. Deutsch *et al.* (2008) point out that in contrast, insect species at higher latitudes – where the temperature increase is expected to be higher – have broader thermal tolerance and are living in cooler climates than their physiological optima. Warming may actually enhance the performance of insects living at these latitudes. It is therefore likely that tropical agroecosystems will suffer from greater population decrease and extinction of native pollinators than agroecosystems at higher latitudes.

Future temperature increase in the tropics, although relatively small in magnitude, is likely to have more deleterious consequences than changes at higher latitudes.

Figure 1.2

PREDICTED IMPACT OF WARMING ON THERMAL PERFORMANCE OF INSECTS IN 2100



On the basis of patterns in warming tolerance, climate change is predicted to be most deleterious for insects in tropical zones.

Source: Deutsch *et al.* 2008.

Coope (1995) gives three possible scenarios for species' responses to large-scale climatic changes:

- Adaptation to the new environment
- Emigration to another suitable area
- Extinction

The first response is unlikely, since the expected climate change will occur too rapidly for populations to adapt by genetic change (evolution). As temperatures increase and exceed species' thermal tolerance levels, the species' distributions are expected to shift towards the poles and higher altitudes (Deutsch *et al.* 2008; Hegland *et al.* 2009). Many studies have already found poleward expansions of plants (Lenoir *et al.* 2008), birds (Thomas and Lennon 1999; Brommer 2004; Zuckerberg *et al.* 2009) and butterflies (Parmesan *et al.* 1999; Konvicka *et al.* 2003) as a result of climate change. Crop species and managed pollinators may easily be transported and grown in more suitable areas. However, moving food production to new areas may have serious socio-economic consequences. In addition, wild pollinators might not be able to follow the movement of crops.

Insect pollinators are valuable and limited resources (Delaplane and Mayer 2000). Currently, farmers manage only 11 of the 20 000 to 30 000 bee species worldwide (Parker *et al.* 1987), with the European honey bee (*Apis mellifera)* being by far the most important species. Depending on only a few pollinator species belonging to the *Apis* genus has been shown to be risky. *Apis*-specific parasites and pathogens have lead to massive declines in honey bee numbers. Biotic stress accompanied with climate change may cause further population declines and lead farmers and researchers to look for alternative pollinators. Well-known pollinators to replace honey bees might include the alfalfa leaf-cutter bee (*Megachile rotundata*) and alkali bee (*Nomia melanderi*) in alfalfa pollination (Cane 2002), mason bees (*Osmia* spp.) for pollination of orchards (Bosch and Kemp 2002; Maccagnani *et al.* 2003) and bumblebees (*Bombus* spp.) for pollination of crops requiring buzz pollination (Velthuis and van Doorn 2006). Stingless bees are particularly important pollinators of tropical plants, visiting approximately 90 crop species (Heard 1999). Some habits of stingless bees resemble those of honey bees, including their preference for a wide range of crop species, making them attractive for commercial management.

Pollinator limitation (lack of or reduced availability of pollinators) and pollen limitation (insufficient number or quality of conspecific pollen grains to fertilize all available ovules) both reduce seed and fruit production in plants. Some crop plants are more vulnerable to reductions in pollinator availability than others. Ghazoul (2005) defined vulnerable plant species as:

- having a self-incompatible breeding system, which makes them dependent on pollinator visitation for seed production;
- being pollinator-limited rather than resource-limited plants, as is the case for most intensively grown crop plants, which are fertilized; and
- being dependent on one or a few pollinator species, which makes them particularly sensitive to decreases in the abundance of these pollinators.

Food production in industrialized countries worldwide consists mainly of large-scale monocultures. Intensified farm management has expanded at the cost of semi-natural non-crop habitats (Tilman *et al.* 2001). Semi-natural habitats provide important resources for wild pollinators such as alternative sources of nectar and pollen, and nesting and breeding sites. Especially in the United States, many of these intensively cultivated agricultural areas are completely dependent on imported colonies of managed honey bees to sustain their pollination. The status of managed honey bees is easier to monitor than that of wild pollinators. For example, bee numbers and diurnal activity patterns can be easily assessed by visually inspecting the hives. Although not commonly used by farmers, scale hives can yield important information on hive conditions and activity, the timing of nectar flow and the interaction between bees and the environment (http://honeybeenet.gsfc.nasa.gov).

In most developing countries, crops are produced mainly by small-scale farmers. Here, farmers rely more on unmanaged, wild insects for crop pollination (Kasina *et al.* 2009). To identify the most important pollinators for local agriculture, data on visitation rate alone does not necessarily suffice. Crop species may be visited by several species of insects, but several studies have shown that only a few visiting species may be efficient pollinators. An effective pollinator is good at collecting, transporting and delivering pollen within the same plant species.

In a recent review, Hegland *et al.* (2009) discussed the consequences of temperature-induced changes in plant-pollinator interactions. They found that timing of both plant flowering and pollinator activity seems to be strongly affected by temperature. Insects and plants may react differently to changed temperatures, creating temporal (phenological) and spatial (distributional) mismatches – with severe demographic consequences for the species involved. Mismatches may affect plants by reduced insect visitation and pollen deposition, while pollinators experience reduced food availability.

We have found three studies investigating how increased temperatures might create temporal mismatches between wild plants and their pollinators. Gordo and Sanz (2005) examined the nature of phenological responses of both plants and pollinators to increasing temperatures on the Iberian Peninsula, finding that variations in the slopes of the responses indicate a potential mismatch between the mutualistic partners. Both *Apis mellifera* and *Pieris rapae* advanced their activity period more than their preferred forage species, resulting in a temporal mismatch with some of their main plant resources (Hegland *et al.* 2009). However, Kudo *et al.* (2004) found that early-flowering plants in Japan advanced their flowering during a warm spring whereas bumble bee queen emergence appeared unaffected by spring temperatures. Thus, direct temperature responses and the occurrence of mismatches in pollination interactions may vary among species and regions (Hegland *et al.* 2009).

Memmot *et al.* (2007) simulated the effects of increasing temperatures on a highly resolved plant-pollinator network. They found that shifts in phenology reduced the floral resources available for 17 to 50 percent of the pollinator species. A temporal mismatch can be detrimental to both plants and pollinators. However, the negative effects of this changed timing can be buffered by novel pollination interactions. Intensively managed monocultures usually provide floral resources for a limited time period. The survival rate and population size of the main pollinators may decrease if the foraging activity period is initiated earlier than the flowering period of the crop species. A loss of important pollinators early in the season will reduce crop pollination services later in the season. In such cases, introducing alternative food sources might be an option for farmers. In more heterogeneous agroecosystems, which are characterized by a higher diversity of crops and semi-natural habitats, pollinators may more readily survive on other crops and wild plants while waiting for their main food crop to flower.

We find the empirical support for temporal mismatches to be weak because of the limited number of studies available in the literature. Spatial mismatches between plants and their pollinators resulting from non-overlapping geographical ranges have not yet been observed. Despite the possibility of moving crop species to areas of suitable climate, we still believe that spatial and temporal mismatches between important crop species and their pollinators are highly probable in the future. Temporal mismatches and lack of synchronicity in plant and animal phenologies are likely because crop plant phenologies probably respond to climate variables in comparable ways to wild plants. Spatial mismatches may also be likely because of the socio-economic costs and consequences of moving food production to new areas, particularly in impoverished countries with high population density and a high degree of pollinator dependence for food production(Ashworth *et al.* 2009). Therefore, it is of the utmost importance for global food production and human well being that we understand the effects of climate change on animal-pollinated crops in order to counteract any negative effects.

Temporal mismatches are likely because crop plant phenologies probably respond to climate variables in comparable ways to wild plants. Spatial mismatches may also be likely because of the socio-economic costs of moving food production to new areas, particularly in impoverished countries.