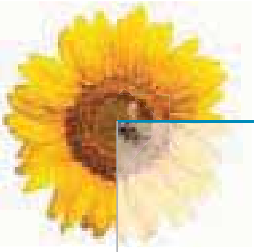




# DATA NEEDS AND RECOMMENDATIONS

To be able to sustain (and increase) agricultural production, it is important to provide precise information on the potential impacts of different climate change scenarios on crop pollination. However, research on the potential effects of climate change on crop pollination is limited. It is therefore urgent that targeted data sampling focus on temperature sensitivity of important entomophilous crops, their most important pollinators and the interactions among them. Basic knowledge of species' climate sensitivity will be important to guide policy makers and farmers in sustaining and managing insect-pollinated agroecosystems affected by climate change. A recent review by Hegland *et al.* (2009) suggests the potential for warming-caused temporal mismatches in wild plant-pollinator interactions. We believe this to be a likely outcome for crop pollination as well. Data should be gathered to enable stakeholders to assess the potential for mismatches in pollinator-dependent agroecosystems and suggest actions to minimize negative effects.

*It is urgent that targeted data sampling focus on temperature sensitivity of important entomophilous crops, their most important pollinators and the interactions among them.*

To enable policy makers, the agricultural industry and local farmers to adapt their practices for production of entomophilous crops under novel climate conditions, we suggest two approaches. The first is to design standardized sampling protocols and gather data on climate sensitivity in crops and their pollinators. The second is to conduct targeted experiments on the temperature sensitivity of entomophilous crops and their most important pollinators. However the extent of data collection required to provide in-depth knowledge on crop pollination may not be feasible in many developing countries because of insufficient financial and human resources. We therefore suggest a simple risk assessment to identify each country's vulnerability to reductions in crop pollination as a result of global warming (Annex 1).

## STANDARDIZED SAMPLING PROTOCOLS

Changes in single-species distributions, local species diversity and the status of ecosystem services such as pollination can be difficult to detect because of the large amount of data needed for precise monitoring. For pollination services, this is further complicated by the large spatio-temporal variation in the composition of plant-pollinator systems (Nielsen 2007; Olesen *et al.* 2008; Petanidou *et al.* 2008; Dupont *et al.* 2009; Lazaro *et al*. 2010). Although focusing on wild plants, these studies have shown that the composition of the pollinator community and the interactions between plants and pollinators are highly variable in space and time. Interactions that are extremely important one year might be nonexistent the next, and plants that appear to be specialized to a single pollinator species might show a high degree of generalization if observed over an extended period of time. In agroecosystems that depend on wild pollinators, information on natural variation in pollinator assemblages is critical. If the extent of natural variation is not corrected for, short-term (natural) variation might be interpreted as climate-induced variation, which could lead to premature conclusions. Although not prone to variations in the composition of the pollinator assemblage, agroecosystems that depend solely on domesticated pollinators (honey bees) will need extensive monitoring to cover naturally occurring temporal and spatial variations in levels of pollination service. To meet the challenges that climate change will pose to crop pollination worldwide, standardized research methodologies must be developed to assess the abundance, diversity, interactions, distribution, phenology and temperature sensitivity of global pollinators and crop species. Such standardized sampling protocols will allow direct comparison of records across time and space (Westphal *et al.* 2008).

The aim of monitoring current agroecosystems is to clarify the relationship between crop yield and pollinator services, and determine how this relationship is affected by climate variables. Here we list some important biological, ecological and climatic factors that we believe should be included in monitoring programmes to better understand the impacts of future climate change on animal-pollinated agroecosystems. We suggest that data-sampling protocols focus on gathering data on the following factors.

## Pollinator activity

In order to understand the nature of crop pollination, it is necessary to have precise information on the pollinator species involved. There are several ways of assessing the status of pollinator species and communities, and the structure of pollination networks (Committee on the Status of Pollinators in North America 2007). Two effective methods have been identified to estimate bee species richness (a useful proxy for measuring the diversity of pollinator communities in many areas): pan traps and transect walks (Westphal *et al.* 2008). Pan traps passively collect all insects attracted to them without assessing their floral associations or whether they pollinate crop species. They can, however, be an effective method for estimating relative population size and species richness as they collect a large number of individuals with little effort. The effectiveness of pan traps in collecting other types of pollinators such as butterflies and hoverflies has not been assessed to the same extent as for bees.

Since pollination depends upon the number of visits provided by each pollinator as well as the pollinator's effectiveness in transporting pollen from anthers to stigmas, pan traps are an inferior method in pollination studies. The visitation frequency of pollinators can be measured by observing and counting pollinators foraging on flowers. Transect walks, which can be used to capture insects visiting crop flowers, are in some ways a better method than pan traps, although more laborious (Westphal *et al.* 2008; Vaissiere *et al.* 2011).

While bees (especially honey bees) are the most frequent visitors to crop plants worldwide, the composition of pollinator communities may vary both locally and regionally. Therefore, a detailed investigation of the composition of each pollinator community is needed. Transect walks also capture pollinators other than bees without creating extensive sampling bias and provide information on specific pollination interactions - a prerequisite for building pollination networks. We recommend transect walks within agricultural fields to assess the status of pollinator communities of entomophilous crops. It is especially important to train field workers in sampling techniques and pollinator taxonomy since variations in skill have been shown to induce bias and reduce data quality. In addition to visitation frequencies, data on the quality of each visit is important for measuring the effectiveness of pollination. It is crucial to estimate each pollinator species' ability to carry pollen from anthers to stigmas (see section on experiments below, page 21). It may be that the species with the highest number of visits is not the most important to plant reproduction. In addition, information on pollinators' additional habitat requirements (e.g. nesting sites), behaviour, life histories and population dynamics is needed to understand the impacts of climatic change on pollinator services to crop plants.

## Temperature sensitivity of pollinators and crops

Local temperature can affect pollinator behaviour, altering the number of visits conducted by a single pollinator and pollinators' behaviour within flowers. On a larger scale, changes in temperature over the entire season may alter the abundance and diversity of pollinators. For example, pollinators with a narrow temperature tolerance may be replaced by other pollinators that are less sensitive to temperature changes or have higher optimal temperatures. Meteorological observations must be recorded to identify correlations between insect activity and climate variables such as temperature, humidity, wind and solar radiation.

Knowledge of pollinators' temperature sensitivity (see section on experiments below) is especially important since it enables us to predict how different climate scenarios may affect the species' behaviour, phenology and distributional ranges. In addition, microclimatic limits for managed bees can be identified by hive monitoring: the total number of bees absent from the hive or nest is measured rather than the number present at a foraging site. At the hive, the number of bees absent from the colony can be estimated from a continuous sequence of counts of arrivals and departures per unit time.

Temperature sensitivity (ranges) of important crops can be obtained from FAO's ECOCROP database (http://ecocrop.fao.org/ecocrop/srv/en/home). This database contains information on more than 2 000 crop species and is continuously updated and expanded.

## Surrounding vegetation (including floral and other critical resources such as nesting sites)

Vegetation surrounding fields of entomophilous crops must be conserved and managed to maintain wild pollinators within agricultural landscapes. It is particularly important to conserve additional food resources for the periods when the crops are not flowering. We therefore suggest that transect walks be conducted in the natural and semi-natural plant communities surrounding agricultural fields (Westphal *et al.* 2008). Quantification of plant and pollinator communities in remnant habitats is needed to assess the viability of pollinator populations, as they likely depend on wild flower resources when crop species are not in bloom. It is also important to monitor ecosystems' resilience to perturbations such as increased temperatures.

In agroecosystems depending on wild pollinators, pollinator diversity and the structure of pollination networks – including wild flowering plants outside agricultural fields – have been shown to buffer against the negative effects of perturbations. Ecosystems with high species diversity are considered to be more resilient to disturbance than less diverse systems. With respect to crop pollination, several studies have indicated that agricultural fields in close proximity to natural habitats may benefit from pollination of native pollinators (Klein *et al.* 2003; Ricketts 2004; Greenleaf and Kremen 2006; Morandin and Winston 2006; Gemmill-Herren and Ochieng 2008) – but see Chacoff *et al*. (2008). Ricketts *et al.* (2004) found that pollination by a diverse group of wild bees enhanced coffee production as several bee species compensated for a drop in honey bee visitation in certain years. Although we could not find any studies on temperature sensitivity in relation to pollination and climate change, we can assume that relying on a few pollinator species is more risky than conserving a diverse pollinator fauna with differing optimal temperature ranges.

A recent study by Thylianakis *et al.* (2010) discusses the properties of pollination networks that might confer robustness in spite of perturbations. These measures, including degree distribution, connectivity and nestedness, can also describe how "healthy" the pollination system appears to be. These indicators should be calculated based on data gathered in monitoring programmes to assess the status of the entire plant pollinator system in the area.

Habitat requirements are species-specific so data must be collected on habitat and food requirements during the pollinators' entire life cycle. Ground-nesting solitary bees and bumblebees seem to prefer sunny, open undisturbed meadows, field margins, sun-drenched, undisturbed patches of bare soil, roadsides, ditch banks and woodland edges (Delaplane and Mayer 2000). Whenever the diversity of native plants is lost, crops that are rich bee forage could be planted to sustain food resources throughout the pollinators life cycles (these include lucerne, clover, oilseed rape and sunflower) (Delaplane and Mayer 2000). Regular mowing is advisable to prevent bee sanctuaries from turning into forests and shrublands. In temperate regions, mowing should be done in winter, when it is less likely to destroy active bumblebee colonies (Delaplane and Mayer 2000).

Non-crop floral resources can be monitored by conducting transect walks in which pollinator interactions in remnant habitats are recorded or by quantifying the amount of floral resources with standardized vegetation-mapping techniques. Monitoring should be undertaken throughout the season (or the entire year in non-seasonal environments) to identify potential periods of floral resource shortage. Bees can be partitioned into guilds on the basis of their nesting habits (Table 2). The availability of nesting sites can be assessed by investigating important habitat characteristics in the surrounding vegetation, such as soil texture, soil hardiness, soil moisture, aspect and slope, amount of insulation, cavity shape and size and diameter of pre-existing holes.

## Climate variables

The most relevant climate variables may vary among crop and pollinator species, and among different climate regions. The first step is to identify the most important variables for each, and then record these variables in the most appropriate way. Environmental cues controlling the phenology of important pollinators might include maximum daily temperature, lack of frost, number of degree days (number of days with a mean temperature above a certain threshold), day length and snow cover. It is also important to record climatic data in the area where the crop pollination system is studied (e.g. average temperature, precipitation, snow cover) to identify other areas where the results might be similar.

Table 2

**HABITAT REQUIREMENTS AND TAXONOMIC GROUPS OF THE DIFFERENT NESTING GUILDS OF POLLINATORS**

| NESTING POLLINATOR GUILDS | NESTING HABITATS | TAXONOMIC GROUPS |
|---|---|---|
| MINERS | Open habitats.<br>Excavate holes in the ground. | Andrenidae, Melittidae, Oxaeidae and Fideliidae.<br>Most of the Halictidae, Colletidae and Anthophoridae. |
| MASONS | Pre-existing cavities, pithy or hollow plant stems, small rock cavities, abandoned insect burrows or even snail shells | Megachilidae |
| CARPENTERS | Woody substrate | Two genera within Apidae (*Xylocopa* and *Ceratina*) and one within Megachilidae (*Lithurgus*) |
| SOCIAL NESTERS | Pre-existing cavities | Apidae: honey bees, bumblebees and stingless bees |

*Source*: O'Toole and Raw 2004.

## Temperature

Pollinators and plants have different climatic requirements, and may therefore respond differently to changes in ambient temperature. Temperature can induce different responses in plants and pollinators. For example, increased spring temperatures may postpone plant flowering time while pollinators might be unaffected. Even if plants and pollinators do respond to the same temperature cue, the strength of the response might differ (Hegland *et al.* 2009). Data on the number of degree days, or maximum temperature during the day or hours with temperature above or below a certain threshold may be more important for crop plants and pollinators than temperature during observations of pollinator activity. Tropical pollinators may respond to different temperature cues than pollinator species at higher latitudes. Temperature-induced activity patterns may also differ depending on pollinator size, age and sex. Winter temperature might also be of importance for pollinators. In recent years, bumble bee hives in Ireland have been able to survive over winter, presumably due to increased winter temperatures (Anke Dietzsch, pers. comm.). These hives will be able to present larger populations of workers at an earlier stage in spring than hives built from scratch by a single queen.

### Precipitation

High precipitation may limit pollinators' foraging activity. Optimal foraging conditions for pollinators are sunny days with low wind speed and intermediate temperature. Climate change is expected to alter existing precipitation patterns. Some areas will likely experience decreased rainfall, leading to more extensive drought periods. This water stress may decrease flower numbers and nectar production. Snow cover might also be reduced with increased temperatures. Indeed, bumblebees have been shown to respond more to snow cover than to temperature (Inouye 2008). In each case, the most relevant measure of precipitation must be assessed.

### Extreme climate events

Extreme climate events might have detrimental effects on both crop plants and pollinator populations. High temperatures, long periods of heavy rain and late frost may affect pollinator activity either by reducing population sizes or by affecting insect activity patterns. The probability of extreme climate events may change in the future. Risk assessments should be conducted to better understand the changes in frequency of extreme climate events and minimize the effects.

## Other threats to pollination services

Pollination is under threat from several environmental pressures. Climate change is only one, and it cannot be seen in isolation, but should be addressed in relation to other pressures affecting plant-pollinator interactions. Here we list some of the most important pressures to be assessed in order to understand how crop pollination might be affected by climate change.

### Agricultural practices

Agricultural intensification by covering large areas with monocultures increases agroecosystems' vulnerability to climate change. Adaptation strategies at the farm level can include increased farm diversity, including crop diversity, and changes in sowing date, crops or cultivars. Greater crop diversity can decrease crops' vulnerability to climate variability, as different crops respond differently to a changing climate. Regional farm diversity may also buffer against the negative effects of climate change at a large scale as it entails a large variability in farm intensity and farm size (Reidsma and Ewert 2008).

## Invasive species

Invasive species may benefit from climatic changes and proliferate in their new habitats. Climate change is predicted to increase invasion of alien species, especially in northern regions. However, the effects of climate change on invasive species and pollination interactions may vary depending on the species and ecosystem in focus (Schweiger *et al.* 2010). It is necessary to assess the controllability of invaders in order to assist policy makers in ranking threats from different invasive species for more effective use of limited resources (Ceddia *et al.* 2009).

## Pest species, pesticides and pathogens

Some invasive insect and plant species are pest organisms, which may cause severe damage to agricultural production. It is expected that climate change will affect various types of pests in different ways (Garrett *et al.* 2006; Ghini and Morandi 2006). Increased temperatures may speed up pathogen growth rates. Warming may also favour weeds in comparison to crops and increase the abundance, growth rate and geographic range of many crop-attacking insect pests (Cerri *et al.* 2007). Increased demand for control of plant pests often involves the use of pesticides, which can have negative impacts on human health and the environment (Damalas 2009), including ecosystem services such as pollination. Diffenbaugh *et al.* (2008) assessed the potential future ranges of pest species by using empirically generated estimates of pest overwintering thresholds and degree-day requirements along with climate change projections from climate models.

Pollinators are also negatively affected by predators, parasites and pathogens. Natural movements of pollinator species and exchanges of domesticated bees among beekeepers will bring them into contact with new pathogens. Pests and pathogens may find new potential hosts (Le Conte and Navajas 2008). It is therefore important to conserve the genetic variability among and within important pollinator species (including races and varieties) to decrease disease-mediated mortality. Managed pollinators may need veterinary aid and appropriate control methods to prevent catastrophic losses (Le Conte and Navajas 2008).

## EXPERIMENTS ON EFFECTIVENESS AND CLIMATE SENSITIVITY OF PARTICULAR SPECIES

The most important pollinators for particular crop species can be identified through monitoring programmes, at least in terms of visitation frequencies. Natural and laboratory experiments can then be conducted to identify the optimal climate conditions and climate toleration limits of target species, and their most important pollinators. When the relationships between climate variables and crop species phenologies have been established, these results can be coupled with those from experiments on single-pollinator species responses with the same climatic variables. From these experiments, it will be possible to assess the potential for mismatches and other altered pollination services resulting from climate change.

Experimental manipulations of climate variables on crop plants and their pollinators enable us to more precisely forecast the impacts of future climate change on crop pollination as they may reveal precise estimates of species' climate sensitivity and the interactions among them. Here, we list potential responses to climate change that can be assessed in experiments on crop plants and their pollinators. We do not provide any detailed experimental setup, but present focal areas where targeted research should be done.

### Identification of important pollinators

Through intensive monitoring, the most frequent visitors to a particular crop species can be identified. However, pollinators vary in their effectiveness in initiating seed set. Fidelity to particular plant species, body size and morphology, and physical movement within and among flowers all affect pollination quality. The importance of each pollinator species is a product of the visitation frequency and the quality of each visit. Visitation quality of the most frequently observed pollinators should be investigated by presenting flowers to single visits of particular pollinator species.

### Crop plant responses to climate change scenarios

#### Changes in nectar and pollen amounts and quality

Pollen quality may change along with climatic conditions. It can be assessed by measuring post-pollination events such as counting the pollen germination rate on stigmas, measuring pollen tube growth and competition, and counting the survival of fertilized ovules, developed embryos and seed and fruit abortions (Dafni 1992). Changes in nectar quantity and quality can be measured at controlled temperatures in climatic chambers. Nectar volume can be measured by inserting calibrated microcapillaries into each flower and nectar concentration can be measured with a pocket refractometer (Petanidou and Smets 1996).

### Changes in phenology

Crop flowering phenology can be manipulated by altering climatic variables (temperature, precipitation, etc.). Important phenological events include the timing of flowering (e.g. duration and date of the first and last flowering), and frequency of flowering. Climate change can be simulated by distributing experimental plots along natural climatic gradients or by creating different climatic conditions in artificial environments such as laboratory or greenhouse experiment.

## Pollinator responses to potential climate change scenarios

Pollinators may respond to climate change in different ways, depending on the system under study and climatic variable in focus. Pollinators may also respond in different ways depending on whether the scale is individuals vs. populations or local vs. landscape.

### Changes in pollinator behaviour

Pollinators may change behaviour in response to shifts in climate. Observations of pollinators in experimentally warmed greenhouses reveal behavioural responses to climate change that may be important for flower visitation. The time taken for thermoregulation at higher temperatures comes at the cost of foraging, with negative consequences for pollination. It is likely that pollinators will change their activity patterns as temperature increases, in turn changing the efficiency of pollen removal and deposition. For this reason, it is important to investigate taxonomic differences in pollinators' ability to regulate body temperature and avoid overheating.

Climate change may also impact activity patterns of pollinators. As temperatures increase, pollinators are at risk of overheating, particularly in regions where current ambient temperatures are high and climatic conditions are stable. In these regions, pollinators such as bees have a body temperature close to the ambient temperature and have a narrow thermal tolerance. Bees have different mechanisms for avoiding overheating, such as shade seeking and prolonged time spent in the nest. Bumblebees are particularly prone to overheating if temperatures increase because of their large size, dark colour and hairy bodies.

## Visitation quality

Experimental manipulation of pollinator assemblages and simulated pollinator species shift can reveal changes in pollination quality. Numerous measures can be used to assess the visitation quality of pollinators (Dafni 1992), but for crop pollination, we suggest focusing on variables related to food production (e.g. seed set or fruit set).

## Changes in pollinator distribution

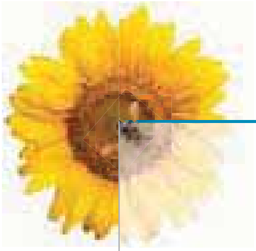
Studying changes in entire pollinator communities is extremely difficult because of the large space and time requirements of such experiments. We have been involved in several studies in which the pollinator activity in plots of wild plants was experimentally reduced (Totland and Lazaro unpublished data). Our preliminary results show that by using "semi-exclosures" around vegetation plots, the number of flower visitors was reduced significantly but not completely. Such alterations in the pollinator community can provide data on the potential effects of changes in the distribution and abundance of pollinator species. Seasonal shifts within (Stone *et al.* 1995) and across species (Potts *et al.* 2003a; Potts *et al.* 2003b) have also been detected in regions with distinct seasons and may simulate species turnover when local climatic conditions change.

Corbet *et al.* (1993) have developed a robust predicative model to obtain a comparative index of pollinator microclimate tolerance based on simple field measurements that do not require specialized instrumentation. They recommend measuring the thermal threshold for profitable foraging flight. Bee activity and microclimate should be recorded at intervals over time. Regression analysis can then be used to model the observed relationship between the available pool of active bees and microclimatic conditions. Estimation of the magnitude of the pool of potential foragers on a given day in a colony of social bees can be expressed by instantaneous counts of active individuals as a percentage of the highest count for that species in each dataset. The ultimate microclimatic limits for sustained flight activity are species specific, and may also differ between subspecies, races and populations of pollinators. Pollinators use several patches during the day for activities such as foraging, and the microclimatic limits may differ between these patches.

## The economic value of crop pollination

Information on visitation frequency and subsequent seed set is valuable when categorizing crops according to their degree of dependence on crop pollination (Delaplane and Mayer 2000). However, the total value of pollinators' ecosystem services at both local and larger scales is little understood. A protocol for assessing pollination deficits in crops has been developed by FAO in collaboration with other institutions (Vaissière *et al.* 2011). Experiments carried out using such protocols will identify crop species under threat of pollination failure in different regions. Further research focused on vulnerable species can identify actions to minimize negative effects.

A recent report published by FAO can be used as a tool for assessing the value of pollination services at a national or larger scale, and vulnerabilities to pollinator declines (Gallai and Vaissière 2009).





# CONCLUSIONS

Although concern has been raised about negative effects of climate change on the services provided by pollinating insects, there is still a paucity of scientific literature regarding how pollination interactions may be affected. In line with the recent review by Hegland *et al.* (2009), we found few studies on this topic with respect to crop pollination. The scientific literature provides numerous examples of climate-driven changes in species distribution and several bioclimatic models have been developed. However, when it comes to research on species interactions – especially interactions between pollinators and crop plants, which account for 35 percent of global food production – there is still a lack of information.

In this report, we have focused on types of data that should be collected to fill gaps in our knowledge of how crop pollination may be affected by climate change. An important first step will be to develop standardized protocols for data collection, including precise definitions of sampling techniques, to compare data through time and between countries. Climate change may affect the phenology and distribution ranges of both crop plants and their most important pollinators, leading to temporal and spatial mismatches. It is therefore important to identify the temperature sensitivity of the most important pollinators and their crop plants, and the environmental cues controlling the phenology and distribution of the identified species. Long-term monitoring of agroecosystems and experimental assessments of species' climate sensitivity may enhance our understanding of the impacts of climate change on crop pollination. Collecting data for these studies is time and resource intensive, which presents a major challenge in countries where the effects of climate change on crop pollination are expected to be most severe (i.e. developing countries in the tropics). In light of the lack of comprehensive information, we have outlined a simple risk-assessment procedure to determine a country's vulnerability to climate-driven effects on crop pollination in the absence of extensive data (Annex 1). It is hoped that through this review, and the tools and approaches suggested, a pro-active risk evaluation approach can assist countries to plan against losses of pollination services due to climate change.

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