Invertebrate genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

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Although the problems caused by invertebrate pests are well known – and considerable effort and resources are devoted to managing them – the vital contributions that invertebrates make to agriculture and food security are often overlooked.

Perhaps the most neglected group of all – in research, in farming practices, and in policies and strategies for agriculture and biodiversity – are the soil-dwelling invertebrates (the first of three major groups of invertebrate ecosystem-service providers discussed in this section). Small, out-of-sight and uncharismatic these animals may be, but their significance is enormous. Some larger soil-dwelling invertebrates, such as earthworms, ants and termites, have been described as "ecosystem engineers". They create the physical structures needed to maintain healthy soil communities and for basic soil processes such as water infiltration and storage, and sequestration and cycling of carbon. They help maintain the chemical fertility needed for plant growth. Also vitally important are the invertebrates that process the leaf litter that

NOTE: This section was adapted by Dafydd Pilling from Cock *et al*. (2011).

falls onto the surface of the soil. This subgroup includes a wide variety of species, ranging from tiny nematode worms and single-cell protista to larger animals such as woodlice, millipedes and centipedes. They are the main players in the transformation of freshly dead organic matter into humus and in the progressive release of nutrients. Finally, the smallest invertebrate predators – less than a tenth of a millimetre across and living in and around soil aggregates – stimulate the mineralization of organic matter by preying on micro-organisms.

None of these processes are isolated. Soil invertebrates are bound in complex webs of interaction with each other, with plants, with micro-organisms and with their physical surroundings. Some species are recognized as "keystones" within the soil community; their presence and roles have a disproportionate effect on other organisms. The loss of a keystone species within the soil can result in dramatic changes and impair the provision of ecosystem services on a vastly greater scale.

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In most soil ecosystems, the resident invertebrate species have not been counted, let alone identified and described. The intricate ecological relationships within soil communities, and between them and above-ground biodiversity, remain very poorly understood. Nonetheless, it has become clear that in many agricultural systems, soil invertebrate communities are in decline. This has contributed to increased rates of land degradation, nutrient depletion, loss of fertility, water scarcity and declining crop productivity. Driving forces of the loss of soil biodiversity include the homogenization of agricultural systems, the spread of monoculture crop production, inappropriate use of agrochemicals and excessive soil disturbance caused by continuous tillage.

A second major group of invertebrate providers of ecosystem services are the pollinators. It has been estimated that at least 35 percent of world food production comes from crops that are dependent on insect pollination (Klein *et al*., 2007). Pollinating insects include wild species spilling over from natural or semi-natural habitats close to crop fields, and managed pollinators (usually honey bees) that can be brought in by farmers specifically to provide pollination. Both wild and managed pollinators are in decline – probably as a result of multiple interacting causes, including land-use change (e.g. the loss of flower-rich meadows), increased use of pesticides, socio-economic factors that make beekeeping less attractive, and the spread of the parasitic mite *Varroa destructor* and other pathogens of bees. The situation has caused such concern that it has been described as a "pollination crisis".

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Biological control agents – the natural enemies of pest species – are the third main group of invertebrate ecosystem-service providers. Biological control agents are commonly found in and around the agricultural ecosystems where their target species (i.e. particular pests) live. Almost all crop production systems benefit from the actions of naturally occurring local biological control agents. In addition, biological control agents can be introduced from outside as part of a deliberate strategy to reduce pest numbers. This can be done via permanent introduction of the agent into a new ecoregion (a strategy known as "classical biological control") or via introduction of the agent directly onto specific crops once or more during the cropping cycle (known as "augmentative biological control").

This section focuses on the three groups of invertebrates described above. However, it should also be recognized that some invertebrates are, in their own right, important sources of food and other products used by humans. The most economically significant products obtained from insects are honey and silk. In Western culture, terrestrial invertebrates themselves are not usually regarded as food for humans (apart from snails in some countries), but elsewhere in the world most large, easily gathered, non-poisonous invertebrates are eaten, including grasshoppers and locusts, crickets, cicadas, ants, termites, immature stages of beetles and moths, scorpions, spiders and worms. At present, these invertebrates are mostly gathered from the wild, rather than farmed. Wild invertebrates are a highly abundant and renewable resource and are a good source

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of protein, fats, vitamins and minerals. Collecting them for consumption or sale in local markets involves minimal inputs. For people who have little access to other sources of protein, invertebrates can be important components of the diet, and are often available when other foods are not.

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The potential of cultivating invertebrates as an ecologically sound means of producing human or animal food is now beginning to attract some interest. Compared to traditional vertebrate livestock, insects are generally more efficient at converting food into body mass, reproduce much more rapidly, occupy less space, use less water and produce less greenhouse gas. However, the mass production of invertebrates as food remains only a possibility. Research, testing, market development, supply chains, storage, preparation, promotion and human preferences would all need to be addressed before it could be realized on a large scale.

Effects of climate change on invertebrate genetic resources and their management

Climate change is expected to affect all three of the main groups of invertebrate ecosystem-service providers as well as invertebrate pests. Invertebrates have limited ability to control their body temperatures. Therefore, although some groups such as soil-dwelling organisms are to some degree buffered against the effects of temperature fluctuations in the wider environment, it is likely that rising temperatures will directly influence the distribution of invertebrate species. Many of the challenges associated with the management of invertebrate genetic resources in agriculture in the context of climate change will relate to climate-driven or human-assisted movement of invertebrate species.

Most invertebrates are expected to change their geographical distribution in response to climate change so as to remain in areas to which they are well adapted. This view is strongly supported by sub-fossil evidence of insect distribution during the glaciations and interglacial periods of the Quaternary Period. The sub-fossil record shows little evidence for the evolution of new species or for mass extinctions during the Quaternary. The sub-fossil remains can nearly all be matched to existing species, and the fact that species occur in similar associations implies that their physiological and ecological requirements have not changed significantly. There is evidence from the sub-fossil record that species disappeared at the beginning of the Quaternary, but little evidence for significant mass extinctions since then. This implies that the species that exist today have mostly existed unchanged since the beginning of the Quaternary, and that they have survived repeated glacial and interglacial periods. What the sub-fossil evidence does show, however, is that insect species have been highly mobile geographically. Broadly speaking, the species found in temperate regions during glacial periods are now restricted to cold areas of the subarctic and high

mountains such as the Himalayas. The species found in temperate regions during the warmer periods of the Quaternary are those that we now associate with the subtropics. The implication is clear: species do not adapt to changing climate; they move to areas where they are well adapted.

The current world is very different from that of the early Quaternary Period. Human activities have created barriers to the migration of invertebrate species. These barriers are likely to affect species in natural ecosystems rather more severely than those associated with agro-ecosystems. The movement of the latter is likely to be facilitated rather than hindered by human-induced landscape changes. *In situ* adaptation of invertebrate species is expected to be most marked where movement is not an option (e.g. on low, isolated islands).

It is very difficult to predict how the combined effects of changing temperatures, changing rainfall patterns and elevated carbon dioxide levels will affect invertebrates and their capacities to provide ecosystem services or to act as pests. As yet, few studies have attempted to investigate interactions of this kind. Further complexity is added by the prospect that the other components of the ecosystem with which invertebrates interact – food plants, micro-organisms, etc. – will also be affected by climate change.

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Aided by human activities, the majority of invertebrate pollinators and pests, along with their natural enemies, can be expected to move with their host plants as crop and forage distributions change. However, as invertebrate species differ in their sensitivity to temperature and other climatic factors, the species composition of invertebrate communities will alter as they follow their associated crop or livestock production systems. Sensitivity to day length and other specific habitat requirements also affect the ability of some species to establish themselves at new latitudes.

It has been suggested that, in the future, parts of the world will have novel climates that have no current equivalent anywhere on the planet. This will inevitably lead to novel associations among invertebrate species and novel effects on agriculture. The consequences of such changes are difficult to predict. Some outcomes may be beneficial (e.g. the absence of some pests) and others harmful (e.g. the absence of some useful invertebrates). Human activities, both within agricultural systems and beyond (e.g. destruction and fragmentation of natural habitats), are likely to have a major influence on how invertebrates respond to climate change.

Warmer, shorter winters will mean that many invertebrates become active and start reproducing earlier in the year. Some species may be able to produce additional generations of offspring in a single year, which in the case of herbivores can have a major impact on host plants.

Extreme weather events such as heat waves, droughts and floods – which are predicted to increase in frequency due to climate change – are often followed by pest outbreaks. Among other contributing factors, these outbreaks can occur because the extreme event eliminates or weakens a pest's natural enemies. For example, field data indicate that parasitoids[5] are generally more sensitive than their hosts to climatic extremes and lag behind in population recovery (Thomson *et al*., 2010). There is a danger that climate change will exacerbate such effects as long-standing relationships between pests and their enemies are broken by sequential extremes (e.g. droughts followed by periods of intense rainfall).

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Climate change is expected to have a profound effect on soil invertebrates and the services they provide. Temperature is a key factor regulating many of the biogeochemical processes in which invertebrates participate or by which they are affected, including soil respiration, litter decomposition, nitrogen mineralization and denitrification. Studies have shown that both elevated temperatures and elevated carbon dioxide levels affect the abundance of invertebrate species and the composition of

5 A parasitoid is an organism that spends a significant portion of its life history attached to or within a single host organism, which it ultimately kills (and often consumes).

soil communities (e.g. Jones *et al*., 1998; Briones *et al*., 2009). Some species are better able to adapt than others. For some invertebrates, the ability to migrate down the soil profile to cooler and moister levels will offer an important survival strategy.

Warmer temperatures are likely to alter invertebrate behaviour, including the hunting behaviour of predators and the feeding habits of herbivores. Temperature can also affect the virulence of pathogens that attack invertebrates, and the capacity of host animals to survive the effects of parasitoids. Climate change is likely to involve shifts in rainfall patterns, which will interact with changes in temperature to influence wetting-drying cycles in the soil. In addition, the distribution, growth and physiology of plants are likely to be affected by climate change. Consequent changes in the nutritional composition of leaves will affect the diets of soil invertebrates.

Relationships between plants, herbivorous invertebrates and the natural enemies of these herbivores have developed over long periods of co-evolution. Species at higher trophic levels (predators and parasitoids) are more likely than herbivores to be affected by climate change, because their survival depends on the capacity of the lower trophic levels to adapt. Natural enemies with very specific host ranges – exactly the type of animal favoured for use in classical biological control programmes – may be particularly sensitive because they need to synchronize their life cycles with those of their hosts.

Climate change is expected to cause significant changes in the degree of synchrony between species' life cycles. In fact, even small changes can substantially influence the efficacy of biological control agents on a local scale. Recent studies have revealed that what had appeared to be generalist biological control agent species are often complexes of previously unrecognized specialist species. As specialists are generally more susceptible than generalists to disruption by climatic perturbations, the vulnerability of these biological control agents to the effects of climate change may be greater than previously anticipated.

Individual pollinator species may be affected by a breakdown in the synchrony between their life cycles and those of flowering plants. The diversity of pollinator communities should act as a buffer against reductions in crop yield. However, in the case of crops that are dependent on specialist pollinators, climate change-induced shifts in the location of production or loss of synchrony between pollinators' life cycles and the flowering seasons of plants are likely to cause problems.

Roles of invertebrate genetic resources in coping with climate change

Because of the many ecosystem services that they provide, invertebrates have a key role to play in adapting agriculture to the effects of climate change. The extent to which the individual services provided by invertebrates will be enhanced or impeded by climate change is difficult to predict. However, if invertebrate biodiversity is lost, the capacity of ecosystems to adapt is likely to diminish.

Healthy soils – and healthy, diverse soil invertebrate communities – will be vital to climate change adaptation. For example, earthworms help to maintain soil structure and the availability of water throughout the soil profile. Studies have shown that the presence of these animals can help to alleviate the effects of drought on crop production (e.g. Johnson *et al*., 2011). Studies have also revealed the remarkable ability of diverse soil invertebrate communities to restore the structure of degraded soils (e.g. Barros *et al*., 2004).

The potential for managing soil invertebrates to enhance their beneficial roles has been little explored. Few if any deliberate attempts have been made to introduce soil invertebrates into new countries or ecosystems. Given the potential for such species to become invasive, it is inadvisable to attempt any such introductions until soil ecology is much better understood than it is today. However, every effort should be made to avoid agricultural practices that disrupt resident soil invertebrate communities and the services they provide.

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The presence of a diverse range of predators and parasitoids will tend to decrease the risk that pest populations will explode as their distributions and life cycles shift in response to climate change. The deliberate introduction of biological control

agents is a well-established practice, and has a potential role to play in adapting crop production systems to new pest problems that arise because of climate change. Maintaining predator and parasitoid species with the potential to play this role is essential. Agricultural practices may need to be adapted to avoid damaging effects on invertebrate biodiversity in and around agricultural lands. In the case of organisms used in augmentative biological control, another potential strategy is to breed selectively for strains with desirable characteristics such as greater heat resistance, greater fecundity or a wider range of species hosts. To date, however, selective breeding of biological control agents has rarely been attempted.

In the case of classical biological control agents, the genetic diversity of introduced populations may be relatively low because the introduction was based on a small founder population. This lack of diversity may inhibit the ability of the population to respond to climate change. It may, therefore, be necessary to bring in additional genetic diversity in the form of new introductions from the original home range of the control agent. Another management option is to adapt the agro-ecosystem in such a way as to enhance the effectiveness of biological control agents that might otherwise struggle in changed climatic conditions. For instance, conservation habitats that provide food and refuges for biological control agents can be established next to crop fields. In the case of augmentative biological control, application strategies can also be adapted. For example, biological control agents that are adversely affected by drought can be applied in the evening when conditions are more humid.

It is likely that some pests, as they move into new areas in response to climate change, will at least temporarily "escape" from their natural enemies. This is likely to increase demand for classical biological control agents, especially in places

where the newly established pest population is separated from its original home by a physical barrier such as the sea or a mountain range. For this reason, access to new classical biological control agents is likely to be particularly important for island countries. There is, however, a risk that the uncertainty and volatility that climate change is expected to cause in food supply and prices will reduce the attractiveness of using biological control agents. Because biological control methods operate with some time delay, uncertainty may lead farmers to opt for broad spectrum insecticides and their immediately obvious effects. This use of insecticides would, in turn, have a detrimental effect on biological control agents.

Conservation of both natural ecosystems and diversity-rich farming systems is essential to ensuring that sufficient biological control agents remain available for the future.

At present, and for the foreseeable future, there are no available means of conserving biological control agents *ex situ*. The lifecycles of these animals have no long-term dormant stages such as seeds or spores. The only option would be to maintain populations in culture. However, this would lead to the loss of diversity over time. Thus, biological control agents can only be maintained satisfactorily *in situ*. The most important reservoirs for biological control agent species are agro-ecosystems where management practices do not hinder their survival (e.g. those with little pesticide use). Most biological control agents are also likely to have reservoir populations in natural ecosystems (i.e. those not used for agriculture). Such habitats are likely to harbour additional genetic diversity within known biological control agent species. They may also be home to unknown species with future potential to act as biological control agents. Conservation of both natural ecosystems and diversity-rich farming systems is thus essential to ensuring that sufficient biological control agents remain available for the future. More research is needed before it will be possible to know which ecosystems are particularly important in maintaining which biological control agents.

As land use changes, it may be necessary to protect or develop corridors of suitable habitat that ensure food and nesting resources are available for pollinators.

Maintaining insect species that can provide pollination services for a wide range of crops is also vital to the future of agriculture in the face of climate change. Pollinator populations not only need to be able to cope with changing climatic conditions, they must also be able to provide the pollination services needed to meet increasing demands for food and retain the capacity to adapt to potential changes in the types of crops grown.

The natural habitats of wild pollinator species need to be identified and preserved. As land use changes, it may be necessary to protect or develop corridors of suitable habitat that ensure food and nesting resources are available for pollinators. The presence of areas of natural and semi-natural habitat next to crop fields has been shown to increase the diversity of pollinator populations and enhance the services they provide (e.g. Steffan-Dewenter and Tscharntke, 1999; Morandin and Winston, 2006; Ricketts *et al*., 2008). Deliberate planting of climate-resilient plants that favour pollinators can serve as a means of maintaining the habitats and floral resources needed by wild pollinators and managed bees. An advantage of having a range of (non-crop) food resources available in the landscape is that the diverse vegetation is likely to support a diverse assemblage of pollinators. This is important, as crops with generalized flowers (i.e. flowers that can be pollinated by a range of species) may produce more reliably when a variety of different pollinator species are present (e.g. Hoehn *et al*., 2008). The insurance provided by a diverse assemblage of pollinators may also facilitate adaptation, because different species will have different capacities to respond to climatic changes.

The world's most important managed pollinator species is the honey bee. This reflects the species' adaptability. It can flourish under many different conditions – from arctic to tropical and from rainforest to desert. Climate change may mean that, in any given area, new honey bee races or hybrids that suit local conditions will need to be introduced (e.g. those that are drought resistance or do not abscond).

Another option that may have to be considered in response to climate change is to explore the use of other bee species (or other insects) as managed pollinators. For example, some stingless bees (*Meliponinae*) and stem-nesting solitary bees (*Megachilidae*) can be domesticated and mass bred. Species could be chosen according to their ecological traits and environmental tolerances (e.g. generalist feeding and nesting habits) for use in adapting managed pollination strategies to the effects of climate change. As described above, crops that are dependent on specialist pollinator species may be particularly vulnerable to the effects of climate change. If problems occur, the only option may be to domesticate and manage the specialist pollinators.

It is important to bear in mind that there are some risks involved in using managed organisms in new environments, because they may interfere with native species. This can occur through competition for resources such as food and nest sites or through the introduction of pests or diseases. Alternatively, diseases can spread from native species to introduced managed pollinators. A notorious example was the transfer of the varroa mite from the Asian honey bee to the managed honey bee in Southeast Asia. Infection of honey bee hives with varroa mites is now a global concern. Given such risks, it is extremely important that transfer of managed organisms is based on established risk-assessment procedures.

Many pollinators are able to move over long distances without assistance from humans. However, it is likely that climate change will increase demand for assisted movement of pollinators between countries.

Recent problems with managed honey bee populations have raised awareness of the vulnerability of pollination services. At present, crop pollination is probably limited by a range of factors, operating to different degrees in different locations, and including inappropriate crop management, lack of habitat for pollinators, pesticide use and unfavourable climate. There is a danger that climate change will intensify these problems. Strategies for dealing with them will need to be integrated into management systems at both farm and landscape levels. For example, shifting from monocultures to mixed cropping systems and agroforestry plantations might help reduce the impact of climatic changes by providing pollinators with favourable microclimates and alternative foraging and nesting resources.

Many pollinators are able to move over long distances without assistance from humans. However, it is likely that climate change will increase demand for assisted movement of pollinators between countries. Such transfers have major potential benefits, but can also generate significant problems. International trade in honey bees and their products is governed by relatively new international laws, which provide a framework for protecting the honey bee industry and for legitimate certified trade in honey bees. Sanitary issues are covered by the Terrestrial Animal Health Code of the World Organisation for Animal Health (OIE). No international regulations are yet in place for environmental risks such as displacement of indigenous pollinators.

Conclusions and recommendations

As yet, it is not possible to draw conclusions as to how climate change will affect specific invertebrate species and the services they provide. However, three general conclusions can be drawn. First, it is likely that climate change will disrupt the

use of invertebrates in agriculture (although the exact nature of these disruptions cannot yet be predicted). Second, without interventions to counter them, these disruptions will result in production losses (although the extent of such losses is not yet known). Third, interventions to help invertebrates adapt and continue providing ecosystem services in the face of climate change are justified (although the methods with which to intervene and the policies needed to facilitate the interventions are not yet in place). Priority actions in the fields of scientific knowledge, conservation, use, access and policy are summarized below.

Scientific knowledge

- Knowledge of the services that the various groups of useful invertebrates provide to crop production needs to be improved, especially in the case of wild pollinators of major crops, soil invertebrates and natural biological control agents. Knowledge is particularly lacking in developing countries.
- The responses of invertebrate species, communities and food webs to climate change need to be quantified. It is only within the last two decades that scientists have begun to study the responses of invertebrate species to climate change. Many mechanisms have been identified. However, the combined effects of factors associated with climate change remain poorly understood.
- Further investigation is needed into past climate change in the tropics and its effects on invertebrates. While past climate change events are relatively

well documented in temperate zones (based on tree rings, glaciers and well-preserved sub-fossils), parallel data are largely lacking for tropical zones.

- Taxonomy and genetic characterization of invertebrates found in agro-ecosystems need to be improved, especially for biological control agents and soil invertebrates.
- More studies are needed on the capacity of key species to move in response to climate change, especially the rates of movement of soil invertebrates that do not have a motile stage in their lifecycles and the capacity of biological control agents to track changes in the distributions of their hosts.

Conservation, use and access

- Rearing technologies for use in the domestication of selected wild bee and other pollinator species need to be developed.
- Means of conserving and promoting generalist natural enemies of pests need to be developed. This will require improved knowledge of the movements of these organisms within landscapes and the ways in which their distributions are affected by the availability of resources such as food and refuges.
- The source habitats of pests and their associated biological control agents need to be identified and conserved. Adapting biological control strategies to the effects of climate change will probably require accessing genetic resources in their habitats of origin.
- Mass-production methods need to be developed for some important species of soil ecosystem engineers in order to facilitate experimental evaluation of their use in soil management.
- Further research is needed on the sustainable use and domestication of edible invertebrates. This potentially valuable food resource has been neglected. If it can be developed as a viable alternative to food from other animals, it could help mitigate climate change.

Policy environment

- An overarching strategy that integrates the management of invertebrates with the management of other ecosystem components is needed.
- Guidelines for facilitating and regulating the movement of invertebrate genetic resources between countries need to be developed. These guidelines should build on what is already available for biological control agents, and should include protocols for emergency responses and pest risk assessment.
- As climate change progresses, agricultural production systems are likely to be affected by new invasive pests. Coordinated development of standard protocols for pest risk assessment would facilitate detection efforts and allow timely responses to pest invasions.
- Responses to invasive pests will probably involve release of classical biological control agents. It may be appropriate to consider revising the relevant international phytosanitary standards to account for emergency responses to new invasive threats.

- Specific policies to address the needs of island states for biological control agents may be required, given that such countries are particularly vulnerable to pest invasions and that climate change is likely to increase the threat.
- In implementing the Nagoya Protocol on Access and Benefit-sharing, countries should consider the importance of access to invertebrate genetic resources for use in sustainable agriculture and the very significant role these resources play in efforts to achieve world food security.
- Countries should ensure that the management of invertebrate genetic resources for food and agriculture is well integrated into their national biodiversity programmes.

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