Reproductive Ecology and Conservation of Plant Genetic Resources of the Wild

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Habitat degradation and overexploitation have threatened the sustainability of our plant genetic resources (PGR) growing in the wild. In the absence of any effective conservation efforts, many of them would become extinct in the coming years. Sustainability of any species depends on its successful reproduction and recruitment of new individuals to the population. The stability of the species is threatened when it experiences major constraint(s) in one or several reproductive events. Thus, for successful conservation and management of any vulnerable species, knowledge on reproductive ecology is essential. In the absence of such data any conservation efforts would remain arbitrary and largely ineffective. Amongst the reproductive events, pollination, seed dispersal and seedling establishment are the most critical aspects and a failure in any of them makes the species vulnerable. Identification of reproductive constraints, if any and their effective mitigation are necessary to conserve or recover vulnerable species. Unfortunately, there is hardly any information on reproductive ecology of our wild PGR. It is important to generate data on reproductive ecology to make our conservation efforts more effective and successful. Knowledge on reproductive ecology is also important to monitor the success or failure of any conservation programme.

Key Words: Habitat degradation, Overexploitation, Plant genetic resources, Pollination, Reproductive constraints, Seed dispersal, Seedling recruitment, Vulnerable species

Introduction

Biodiversity includes all heritable variations at all levels of organization (Wilson, 1997). India is bestowed with a vast biodiversity (Bawa, 2010; Uma Shaanker *et al.*, 2010). Although we cover only 2% of the land area, our biodiversity is about 7.5%. India shares four of the 34 biodiversity hotspots with the neighboring countries: i) Western Ghats and Sri Lanka, ii) Himalayas, iii) Indo-Burma (Northeast India south of Brahmaputra, Myanmar, Thailand, Laos, Vietnam and Southern part of China) and iv) Sundaland (Andaman and Nicobar Islands, Malaysia and Indonesia). About one third of our species of higher plants are endemic.

Plant genetic resources (PGR) generally refer to all those plant species being used and also those that have potential use for human needs. Apart from cultivated agri-horticultural species, land races and their wild relatives, PGR includes forest species used for wood as well as those wild species which are the sources of non-wood forest products such as gums, resins, medicines, dyes, biopesticides, bamboos and rattans (Biswas, 2004; Gautam, 2004). Indian subcontinent is the centre of diversification and domestication of a range of economically useful wild plant species. They comprise 3000 species of edible value, 4000 species of medicinal value, 500 fibre-yielding species, 400 fodder species, 300 gum, resin and dye yielding species and 100 species of aromatic and essential oil-yielding species (Pandey and Arora, 2004). These wild PGR are the repository of novel genes for nutrition, resistance to biotic and abiotic stresses, and a range of medicinal and industrial uses. A large number of economically important naturalized and domesticated species introduced from other countries also form an important component of our PGR (Gautam, 2004). Plant genetic resources are fundamental to human welfare and their effective management is crucial for conservation of genetic variability needed for further improvement in the productivity and quality of crops and other plant-based products needed to satisfy human needs in the coming decades (Dhillon *et al.*, 2004). Thus, a diverse array of plant species needs to be conserved and managed for the present and future use of mankind. The National Bureau of Plant Genetic Resources (NBPGR) is the nodal agency for the management of PGR in India; it has made remarkable progress in ex situ conservation of both cultivated and wild species of agri-horticultural importance (Singh *et al.*, 2004).

A large number of species which are being harvested from the wild and also those which have the potential to provide future human needs have to be conserved and effectively managed *in situ* (within their natural habitats) (Dhillon *et al.*, 2004; Abraham *et al.*, 2004; Biswas, 2004). Habitat degradation and/or overexploitation have enormously increased vulnerability of our PGR of the wild in recent decades (Murali *et al.*, 1996; Bekker and

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Berendse, 1999; Pares *et al.*, 2003; Rodriguez-Cabal *et al.*, 2007; Peres, 2010; Bennett and Saunders, 2010; Laurance, 2010; Tandon *et al.*, 2010; Sodhi and Ehrlich, 2010). This is particularly true for tropical forests which harbor most of the world's biological diversity and genetic resources (Herrera and Pellmyr, 2002; Roubik *et al.*, 2005, Dennis *et al.*, 2007; Ghauzol and Sheil, 2010). Some of the causative factors for habitat degradation are: encroachment of forests for agri-horticulture, logging, urbanization and industrialization. As the livelihood of a large number of people in developing countries depends on forests; a range of non-wood forest species are collected extensively from the forests for their livelihood. Increasing population pressure combined with rising standards of living over the years have resulted in overexploitation of wild PGR in our forests and a large number of species have been pushed into vulnerable category (The IUCN Red List of Threatened Species 2008, series of volumes on Red Data Book of Indian Plants since 1987 by the Botanical Survey of India, see also Ravikumar and Ved, 2000; Rao *et al.*, 2003; Pandravada *et al.*, 2004).

A general principal for effective conservation and management of any species is that more we know about the biology of the species, better is the rate of success. A major area of biology which has direct relevance to the conservation of vulnerable plant species is reproductive ecology. This article highlights some aspects of reproductive ecology which are relevant for effective conservation and management of vulnerable, endemic and endangered wild PGR.

Causes for Species Vulnerability

The stability of any wild species essentially depends on its effective reproduction and recruitment of new individuals to sustain populations. Both habitat degradation and overexploitation eventually affect the ability of the species to reproduce and/or to recruit new individuals (Bond, 1994; Robertson *et al.*, 1999; Wilcock and Neiland, 2002; Kwack and Bekker, 2006). Such reproductive constraints gradually result in deaths exceeding births in the populations. When this continues, there is a gradual decline in population size. Continuous reduction in population size leads to eventual extinction of the population/species. In some species, reproductive failure often leads to adaptation to inbreeding/vegetative propagation as a means of reproductive assurance. Although this may ensure short-time survival of the species, it eventually leads to:

- loss of genetic variability
- inbreeding depression
- loss of evolutionary potential to cope with changed habitat and
- eventual extinction of the population.

Reproductive Ecology – Basic Aspects

Reproductive ecology covers a broad spectrum of events involved in reproduction of an organism (Shivanna, 2003) and their interaction with biotic and abiotic components of the environment. Effective conservation measures for vulnerable species depend on our understanding of the nature of threats to the sustainability of the species and their effective remediation. As reproduction and recruitment are the major threats in the final analysis of species stability, generation of baseline data on reproductive ecology is a pre-requisite for effective management of our genetic resources.

The following are the major reproductive events in flowering plants:

- Phenology
- Floral morphology and sexuality
- Pollen and pistil biology
- Pollination ecology
- Pollen-pistil interaction and the breeding system
- Seed biology (seed production, dispersal and viability)
- Seedling recruitment

Although all these aspects are important for a comprehensive understanding of the reproductive ecology of the species, some of the most important areas which are relevant for conservation of PGR are: pollination ecology, breeding system, seed biology and seedling recruitment. The following pages give a brief account of these areas and their relevance for conservation of vulnerable species.

Pollination Ecology

Pollination is the transfer of pollen from the anther to the stigma. Pollination ecology is the study of pollen transfer from the anther to the stigma through an understanding of interactions between plants and pollinators in relation to the prevailing habitat (Jones and Little, 1983; Herrero and Pellmyr, 2002: Roubik *et al.*, 2005). Except in parthenocarpic and apomictic species which are pseudogamous (endosperm development with out fertilization), pollination is an essential requirement for fruit and seed set. Only a small proportion of wild species depend on wind or water for pollination; a vast majority of them depend on animals for pollination. Flowers exhibit an amazing variety of sizes, shapes, colours, arrangements, scents, and sexual systems to attract various animals to the flowers to achieve pollination. Non-mobility is one of the major limitations of plants to move their genes across space; diversification of flowers seems to be necessary to attract various animals to move their genes. Amongst animals, insects are the major pollinators; of these, bees, beetles, moths, butterflies and flies are the most common pollinators. Pollination in animal-pollinated species is largely mutualistic between plants and animals that result in reciprocal benefits to both the partners. It is a form of 'biological barter' in which plants exchange their resources such as pollen and nectar with the pollination services of animals. This mutualism is highly complex, dynamic and varies greatly in time and space. It has become highly vulnerable in recent years as a result of habitat loss.

An understanding of pollination ecology of a species needs familiarity with the phenology (timing of various reproductive events, their duration and intensity) of the species, structural features of flowers and sexuality. Depending on the origin of pollen, pollination is categorized into the following three types:

Autogamy – transfer of pollen from the anther to the stigma of the same flower. Geitonogamy – transfer of pollen from the anther to the stigma of another flower of the same plant or of another plant of the same clone (ramet).

Geitonogamy – transfer of pollen from the anther to the stigma of a different plant (not of clonal origin, genet).

The first two represent self-pollination leading to inbreeding and the third represents cross-pollination. Identification of pollinator(s), their efficiency and pollination limitation, if any, under natural habitats are important components of pollination ecology which determine the extent of success of seed set.

Pollination Limitation

Pollination is a major constraint for optimal seed set in many vulnerable species. Pollination limitation (reduction in seed production by inadequate pollination) is wide spread and also of high magnitude (Burd, 1994; Larson and Barrett, 2000; Wilcock and Neiland, 2002; Knight *et al.*, 2005). When compared to temperate species, tropical rain forests are characterized by longer distances between conspecific plants, higher incidence of self-incompatibility, dependence of a fewer pollinators and lower incidence of vegetative propagation (Wilcock and Neiland, 2002). These features make them more vulnerable to pollination failure when compared to temperate species.

Pollination limitation not only reduces seed set, but also the quality of offspring by reducing pollen competition among gametes (Corlett, 2007). Pollination limitation may be the result of several ecological disturbances such as habitat fragmentation, presence of co-flowering plant species and introduction of alien species (Wilcock and Neiland, 2002; Knight *et al.*, 2005; Kolb, 2005; Aguilar *et al.*, 2006). Pollination limitation is more prevalent in specialized plant species which depend on just one or a few animal species for pollination services. Vulnerable species generally occur in specialized or fragmented habitats in sparse populations. These features amplify pollination limitation; as the distance between plants increases, the resources available for pollinators decreases, leading to a decline of animals involved in pollination (Wilcock and Neiland, 2002). When the plant species happen to have special sexual features such as dioecy and self-incompatibility, which make them depend entirely on cross-pollination for seed set, pollination failure would further intensify. Detailed information on pollination limitation is necessary to come up with an effective strategy to overcome the limitation (Spira, 2001). Significant reduction in recruitment as a result of pollination failure compromises evolutionary adaptability and thus their eventual survival prospects. Pollination can be a limitation even in wind-pollinated species when population density of plant species becomes low (Wilcock and Neiland, 2002).

Pollination Ecology and Release of Genetically Modified Plants

One of the major concerns for the release of genetically modified plants (GMP) has been the possibility of pollen flow from GMP to wild relatives and their introgression into wild populations (Armstrong *et al.*, 2005). Regulatory authorities need extensive data on the biology of GMP (Craig *et al.*, 2008). Of these, pollination ecology of the GMP and their wild relatives is an important component (Marvier, 2008) to rule out the possibility of escape of engineered gene(s) to the wild before permitting GMPs for field trials and their eventual release for cultivation. Every new transgenic organism requires a great deal of research in assessing the following four basic aspects (Armstrong *et al.*, Craig *et al.*, 2008; 2005; Marvier, 2008):

i) Potential of hybridization of transgenics with wild relatives

ii) Rate of hybridization

iii) Opportunities for backcrossing and introgression of transgenes into the wild relatives

iv) Ecological impacts of transgenes in wild populations.

Thus detailed knowledge on various aspects of pollination ecology and its consequences is important before transgenics are released. Assessment of these aspects of GMP involves research into the following aspects of reproductive biology:

- spatial and temporal distribution of other cultivars and wild relatives in the area where the transgenics are grown
- flowering phenology of transgenics and their wild relatives
- temporal details of pollen viability of transgenic plants
- temporal details of stigma receptivity of the transgenics and related species growing in the area
- details of pollination ecology and pollen flow of transgenic plants through biotic and abiotic means
- compatibility relationships between the transgenics and other cultivars/wild species
- details of hybrid seed development, hybrid seedling establishment and potential of development of backcross seeds with wild populations.

Pollination Ecology and Crop Introduction

Knowledge on pollination ecology is important in crop domestication and introduction. Crop introduction to other areas/countries has been one of the approaches for exploitation of genetic resources. When crops are introduced into areas where natural pollinators are absent, introduction of pollinators is one of the effective options for assured pollination. Oil palm (*Elaeis guineensis*), a native of Africa and Central South America, is pollinated by wind as well as many insects particularly weevils. Oil palm was introduced to Malaysia and Indonesia where its pollinators were absent. During the initial years, the yields were low because of inadequate pollination. Introduction of weevil, *Elaeidobius kamerunicus*, the pollinator of oil palm, from Cameroon to Malaysia during 1960s has markedly increased the yield (Syed *et al*., 1982). Now oil palm is one of the most important crops in these countries.

In India also, there are many crops which can be introduced to other areas and exploited. For example, *Amomum subulatum* (large cardamom) is an important cash crop in the North-East particularly in Sikkim, Bhutan, Nepal and Darjeeling areas of West Bengal. Bumblebee is the principal pollinator. Attempts are being made by the Spice Board to introduce this crop to cardamom growing belt of Kerala. Although the plant grows well and flowers profusely, it does not set fruits. Even in the plains of Karnataka (elevation ca 600 msl) *A. subulatum* grows well and flowers but does not set fruits (personal observations). Lack of fruit set in Kerala and Karnataka seems to be due to the absence of the pollinator. It is therefore necessary to study the details of pollination ecology to identify the problems, if any, and develop technology to mitigate the problem before the crop is introduced.

Breeding System

Breeding system is the mode of transmission of genes from one generation to the next through sexual reproduction. It largely reflects the extent of selfing/crossing (Richards, 1986). Genetic variation is the basis of evolution; it enables the species to cope with changed habitat and its establishment when migrated to new areas. Genetic variation is assessed on the basis of the extent of heterozygosity in the population. This is dependent on a number of reproductive traits particularly the sexuality of the species (bisexual/unisexual flowers, monoecious/dioecious plants) and the breeding system (extent of selfing/crossing).

Flowering plants have evolved the following devises to encourage outbreeding and discourage inbreeding:

Dichogamy: Temporal separation of pollen release and stigma receptivity.

> ***Protandry:*** Anthers release pollen before stigma becomes receptive.
>
> ***Protogyny:*** Stigma is receptive before pollen release.

Herkogamy: Spatial separation of the anthers and the stigma.

Self-incompatibility: Self-pollinations do not result in fertilization because of inhibition of pollen germination or pollen tube growth in the pistil.

Dicliny: Flowers are unisexual.

> ***Monoecious:*** Male and female flowers are borne on the same plant.
>
> ***Dioecious:*** Male and female flowers are borne on different plants.

Of these, self-incompatibility and dioecy prevent inreeding completely. In a majority of other species it is a combination of selfing and crossing, although the extent of each varies greatly between and within the species. An understanding of the breeding system of the species is important not only for conservation but also for domestication and introduction of the species to newer areas.

The breeding system of the species (self-compatible/ self-incompatible) has a marked effect on its vulnerability to pollination limitation in fragmented, low density populations (Aizen and Feinsinger, 1984; Kery *et al.*, 2000, Aizen *et al.*, 2002; Lennartsson, 2002). In India, recent studies of Nayak and Devidar (2010) on ten species in the Pondicherry region of southern India have clearly shown a higher level of pollination limitation leading to lower fruit set in self-incompatible species when compared to self-compatible species. This is because self-compatible species are less dependent on pollinators. Further, the sapling and adult densities in self-compatible species were significantly higher than those in self-incompatible species in fragmented habitats indicating that lower fruit set as a result of pollination limitation would lead to lower rate of recruitment. This should be true for dioecious species also. For an effective management of species in fragmented populations we must be aware of the breeding system of the species.

Seed Biology

Seeds provide the species a means not only for increasing genetic diversity (through cross-pollination) but also for independent dispersal which enables the species to establish in new environments (Turner, 2001; Fenner and Thompson, 2005; Dennis *et al.*, 2007). Seed production, therefore, is an essential reproductive event for the long-term stability and spread of the species. Seed biology is, therefore, yet another important aspect of reproductive ecology which has relevance to conservation biology (Khurana and Singh, 2001; Corlett, 2007). Some of the important aspects of seed biology are: seed production and their dispersal, viability of seeds in the soil seed bank and seedling recruitment (Hall and Lulow, 1997; Bustamante and Simonetti, 2000).

Seed Production and Dispersal

Only a small proportion of flowers develop into mature fruits particularly in tree species. There is great variation between species in the extent of fruit and seed set. This seems to be an adaptation to provision a reserve of flowers that can be used under optimal conditions but discarded with minimum cost under suboptimal conditions. Depending on the available resources, the plant can also terminate developing fruits before investing for their full development. The failure of flowers developing into fruits is due to a combination of factors such as pollination limitation, genetic defects, resource limitation, and predation of flowers and young fruits. Both seed limitation (arrival of very few seeds to potential regeneration sites suitable for establishment) and establishment limitation (lack of availability of suitable microsites for seedling establishment) (Nathan and Muller-Landau, 2000; Dalling *et al.*, 2002; Svenning and Wright, 2005; Norghauer and Newery, 2010) play a critical role in sustainability of populations.

Dispersal of seeds is one of the most critical aspects of reproductive ecology; it is an important step for the recruitment and spatial distribution of plant populations. Seed dispersal provides many advantages to plants: escape from specialist predators and pathogens prevalent under the parent, prevention of competition between parent and offsprings and between siblings, and location of seeds in safe sites where they can successfully germinate and establish seedlings (Fenner and Thompson, 2005; Ghauzol and Sheil, 2010). Thus, seed dispersal enables plants to escape from sources of mortality that are concentrated around parents, and increases the probability of colonizing suitable habitats (Dennis *et al.*, 2007).

In general, a majority of seeds fall below the parent plant. A small proportion of them are dispersed away from the plant. Fruits and seeds have adopted a range of devices for effective dispersal. Animals are the major seed dispersers. Because of anthropogenic disturbances as a result of direct persecution (hunting or trapping of species and collection of live animals for pet trade) and land-use changes, many seed dispersers have become endangered in tropical forests. Some of them have almost been eliminated from many of their natural ranges. This is particularly true for large birds, large fruit bats, primates, civets and terrestrial frugivores which are the major dispersers of large-fruited plant species (Dennis *et al.*, 2007).

Although extensive studies have been carried out on seed dispersal in the Neotropics and tropics of Africa, Australia and the Far East (Dennis *et al.*, 2007; Corlett 2007), only a beginning has been made in tropical forests in India. The proportion of animal dispersed species range between 68 to 78% (Datta and Rawat, 2008; Tadwalkar *et al.*, 2012). Birds followed by mammals are the major animal dispersers (Ganesh and Devidar, 2001). The density of animal-dispersed species tends to decrease in disturbed habitats as a result of dispersal limitation since animal dispersers are more severely affected by forest fragmentation. However, the density of species which are not dependent on animals for dispersal tends to increase in such habitats (Tadwalkar *et al*., 2012).

Viability of Seeds in Soil Seed Bank

The period for which seeds remain viable varies greatly, from a few weeks to several years. Although we have extensive data on seed viability and storage of cultivated species, there is hardly any information on PGR growing in the wild. After dispersal from the parent plant, seeds fall on the surface of the soil. They may germinate soon after dispersal or remain dormant for varying periods before germination. Some of them get covered with leaf litter and eventually get buried in surface layers of the soil. The seeds present on or in the soil form the soil seed bank. For the sustainability of the PGR in the wild, viability of soil seed bank is more important then their viability under laboratory conditions. Considerable information is available on soil seed banks of temperate species (Thompson *et al*., 1997). Occasionally, soil seed bank may contain seeds of plants which are no more growing in the region. An interesting example of longevity of soil seed bank is *Nelumbo nucifera*. Several seeds recovered from dried bed of an earlier lake in North-East China germinated and radioactive carbon dating of the oldest germinated seed showed that it is 1288 ± 250 years old (Shen-Miller *et al*., 1995).

Seed persistence in the soil seed bank is a critical trait for species with very low fecundity and those which require more exact conditions for germination and seedling establishing (Gallery *et al.*, 2007). Unfortunately, there is very little information on seed banks of tropical region. A majority of tree species in Western Ghats show fruiting during pre-monsoon drier months or monsoon period. Of the 185 species studied for their fruiting behavior in Northern Western Ghats (Tadwalkar *et al.*, 2012), 64% of the species showed fruiting in the pre-monsoon period (February-May). The seeds of those species which fruit pre-monsoon or during the monsoon months are exposed to monsoon wet season which is suitable for seed germination and seedling establishment before the ensuing drier months. The fruiting synchrony with the wet monsoon months appears to be an adaptation for successful seedling recruitment. Seeds of many species in Western Ghats (for example, *Dysoxylum malabaricum*, *Vateria indica* and several species of *Syzygium*, our unpublished observations), which are shed during the monsoon period germinate within a few days after dispersal and their seedlings are established before the onset of post-monsoon drier months. Seeds of these species are refractory and loose viability within weeks after shedding. Such species do not contribute to the soil seed bank. If they miss the monsoon season, there is zero recruitment. Many of these species also show flowering in alternate years making seedling recruitment more critical. It is, therefore, important to know seed viability in the soil seed bank for effective management or restoration of the species.

Seedling Establishment

Seedling establishment is the final hurdle in a series of reproductive events culminating in the recruitment of new individual. A large proportion of seeds may not germinate as they may not land on suitable microsites. Even when they germinate, seedling mortality is high in wild species. Competition from other seedlings and from surrounding vegetation, herbivory, and infestation by insects, fungi and other microbes are the major causes for seedling mortality. Abiotic hazards for seedling survival include physical damage due to fall of branches, fire and lack of moisture. Detailed information on seed dispersal, seed viability in the soil and constraints for seedling recruitment is necessary for developing effective strategy to conserve and manage the species (Corlett, 2007).

Several studies have indicated that recruitment is the major limitation for population sustainability in several non-wood forest resources of Madhya Pradesh, India. *Sterculia urens*, the source of gum karaya (Indian tragacanth), is an important non-wood forest product of India. It is a source of income to the tribals and the rural poor living around the forests. Secretion of the gum requires wounding of the bark. The tappers use crude method of tapping causing serious injury to the plants. The trees eventually die after repeated and unscientific tapping for several years. Owing to steady increase in the export demand for gum karaya, *S. urens* is over-exploited. Death of old trees and lack of seedling recruitment in the natural habitats have resulted in a large-scale reduction in the populations of *S. urens*. Detailed studies (Sunnichan *et al*., 2004) on reproductive ecology have shown that there are no major constraints in pollination and seed production in this species.

However, recruitment seems to be the major constraint (Sunnichan, 1998; Tandon *et al.*, 2010) for sustainability of the populations of *S. urens*. A large number of vigorously growing seedlings appear under the canopy of parent trees during the monsoon. The seedlings develop underground tubers and the shoot dries up during October-November. A new shoot comes up from the tuber in the next monsoon season and grows for 2-3 months before drying up again. This cycle of shoot death and sprouting of new shoot is repeated for another year before a permanent shoot comes up. The tuber enlarges during each year of shoot growth and sustains early growth of the permanent shoot. However, the tubers are dug up from the forest soil by the surrounding villagers and are cooked and eaten as food or pounded and used to relieve constipation and to facilitate childbirth. Wild herbivores also dig up some tubers and consume them. Harsh drought conditions prevailing during summer may also result in drying up of some of the tubers. Eventually no new adult is added to the population. In another overexploited gum-resin yielding species, *Boswellia serrata* (Sunnichan *et al.*, 2005; Tandon *et al.*, 2010), the source of 'salai guggul', also seed production is satisfactory but seedling recruitment is the major constraint for sustainability of the populations.

Apart from habitat degradation and overexploitation, global warming is an additional factor which is going to play a major role in sustainability of PGR in the future. Limited data available has already shown that global warming affects flowering phenology and induces species migration (Fitter and Fitter, 2002; Jump and Penuelas, 2005; Lovejoy and Hannah 2005; Miller-Rushing and Primack, 2008; Thuiller *et al.*, 2008; Lovejoy, 2010). Such changes are likely to bring bout decoupling of plant-animal mutualisms which are likely to have serious consequences on the sustainability of the species. Understanding the details of spatial and temporal variation in plant-animal mutualisms is necessary to predict the long term effects of global warming.

Conservation Approaches

Conservation involves a) preservation (of what exists) and b) recovery (of populations of endangered species to a sustainable level). In recent years, conservation efforts are being increasingly directed towards habitats and ecosystems, rather than individual species. Establishing protected areas/reserves has been the main approach to conserve and recover the habitat and the populations. Although a large number of protected areas have been established in India, there is hardly any management to check whether it is effective at conserving biodiversity particularly of vulnerable species.

If overexploitation is the only cause for vulnerability of the species, conservation approach is straightforward and involves controlling the harvest from the vulnerable species to a sustainable level. But this approach is difficult to implement and monitor particularly in developing countries because of population pressure. Landscape protection may not be effective in those species in which reproduction or recruitment is seriously compromised due to other reasons. Many of these approaches are species-specific and situation-specific. Effective mitigation of reproductive constraints depends on the availability of detailed information on reproductive ecology of the species. When vulnerability is because of the inbreeding depression, introduction of cross-compatible genotypes may be an effective approach to increase heterozygosity of the population. Also, establishment of new populations at suitable habitats using several cross-compatible genotypes would also be effective in mitigating the constraints (Wilcock and Neiland, 2002). In some species, it may require reintroduction of missing pollinators or dispersal agents, or the reinforcement of depleted populations or reintroduction of populations in suitable habitats. Manual seed dispersal and planting of nursery raised seedlings is an effective approach for reinforcement or reintroduction of populations. The success rate of artificial seed dispersal is relatively low, as a result of seed predation and other post-dispersal processes. Planting of nursery-raised seedlings avoids most of these problems (Corlett, 2007). Another approach to conserve PGR being harvested in the wild such as medicinal plants and sources of other non-wood forest products is to bring them under cultivation for sustainable harvest so that the pressure on the wild germplasm is reduced.

Although there is considerable information on the details of reproductive events on species of Neotropics and the tropics of Africa, Australia and the Far East (Bawa and Hadley, 1990; Turner, 2001; Herrera and Pellmyr, 2002; Roubik *et al*. 2005, Dennis *et al*., 2007), there is hardly any information on reproductive ecology on species of the Indian tropical forests. Therefore, the species-specific conservation approaches mentioned above would largely remain theoretical for India's conservation programme because of our ignorance on reproductive ecology and reproductive constraints, if any, of our vulnerable species. Generation of data on reproductive ecology particularly plant-animal interactions is, therefore, urgently needed for effective formulation and implementation of our conservation programmes. In the absence of such data our conservation efforts would remain arbitrary and largely ineffective.

Concluding Remarks

A perusal of recent books and reviews on conservation biology indicates that scientific conservation attempts made and also some of the successes reported so far are animal- centric (Hayward, 2009; Sodhi *et al*., 2011). There are hardly any success stories on conservation of plant species. It is apparent that several reproductive constraints, particularly pollination limitation, seed limitation and establishment limitation play a critical role in sustainability of the wild populations of PGR. It is important to understand whether any of these limitations are prevalent in the vulnerable species, and if so, the processes and consequences of such limitations for effective conservation and management. Conservation success depends on the quality and quantity of research component on the focal species. Lack of adequate information on reproductive ecology in general and plant-animal interactions in particular, has been the major limitation to formulate and implement effective conservation programmes. Studies on reproductive ecology are important not only for understanding the cause(s) for species vulnerability and its conservation but also to monitor the success or failure of any conservation programme. Such information is also needed in assessment of the risks the species is exposed to and their ability for long-time survival without intervention. Conservation efforts need to be proactive and should be initiated much before the species becomes critically endangered for a reasonable success.

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