Chapter 15

Invasive Agroforestry Trees: Problems and Solutions

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Thousands of plant species have been and continue to be transported by humans to areas far from their natural habitats. Some are moved accidentally, but more important are the many species that are intentionally introduced and cultivated to serve human needs (Ewel et al. 1999). In many parts of the world, some alien plant species (a small sample of all nonnative species in a given region) cause problems as invaders, spreading from sites of introduction and cultivation to invade natural or seminatural ecosystems, where they sometimes cause widespread damage. Biological invasions are now viewed as one of the main threats to global diversity (Sala et al. 2000; McNeely et al. 2001). Invasive plant species, and woody plants in particular, have major impacts on ecosystem structure and functioning (Versfeld and van Wilgen 1986).

The terminology of alien plant invasions used in this chapter follows Richardson et al. (2000b; see also Rejmánek et al. 2004 and Figure 15.1):

- *Alien plants:* Plant taxa whose occurrence in a given area results from their introduction (intentionally or accidentally) by human activity (synonyms: "exotic plants," "nonnative plants," "nonindigenous plants").
- *Casual plants:* Alien plants that may flourish in an area but do not persist for more than one life cycle without further introductions (includes taxa labeled in the literature as "waifs," "occasional escapes," and "persisting after cultivation").
- *Naturalized plants:* Alien plants that reproduce and sustain populations over more than one life cycle without direct intervention by humans (or despite human intervention); they often recruit offspring freely, but often just near adult plants, and do not necessarily invade natural, seminatural, or human-made ecosystems.
- *Weeds:* Plants (not necessarily alien) that are undesirable from a human point of view. These are usually taxa with detectable economic or environ-

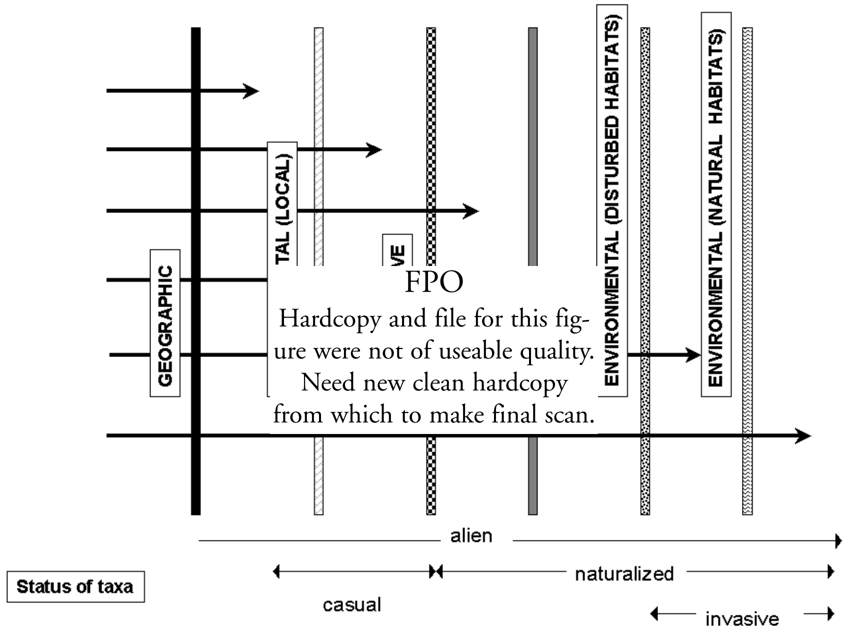

Figure 15.1. A conceptualization of the naturalization-invasion process, showing successive barriers that an alien species has to overcome to become naturalized or invasive (after Richardson et al. 2000b). Each barrier provides options for management of invasive agroforestry trees.

mental effects (synonyms: "pests," "harmful species," "problem plants"). Environmental weeds are alien plant taxa that invade natural vegetation, usually adversely affecting native biodiversity or ecosystem functioning.

- *Invasive plants:* Alien plants that recruit reproductive offspring, often in very large numbers, at considerable distances from parent plants and thus have the potential to spread rapidly.
- *Transformer species:* A subset of invasive plants that change the character, condition, form, or nature of ecosystems over a substantial area relative to the extent of that ecosystem.

Many agroforestry systems, particularly those that rely on tree planting in or near treeless landscapes, rely heavily on alien plant taxa. As is the case in all endeavors based largely on nonnative species, problems arise when these organisms spread from sites of introduction and cultivation to invade areas where their presence is, for various reasons, deemed inappropriate. In some areas, problems caused by the spread of agroforestry trees from sites set aside for this land use pose a serious threat to biodiversity that may reduce or negate any biodiversity benefit of the agroforestry enterprise. The actual or potential impacts caused by such invasions must be weighed carefully against the actual or potential benefits deriving from the use of these alien species.

Very little has been published about invasions as a direct result of agroforestry. Indeed, the very concept of invasion is meaningless or absurd to some agroforesters, especially those working in dry and severely degraded environments. In these situations, recruitment of any woody plant is considered a bonus. A review of the agroforestry literature, discussions with agroforesters, and the authors' experience in many parts of the world reveal that some commonly used trees and shrubs in agroforestry are harmful invaders in some localities, under certain situations. Others that have not yet been reported as invasive are likely, because of their growth and reproductive characteristics, to invade when they are introduced to suitable environments or after the time lag that is usually observed between when a species is introduced and cultivated or disseminated and when it starts to invade. For more than two decades, some of the agroforestry literature has warned about the threats of alien species spreading uncontrollably (BOSTID 1980, 1983). However, Hughes (1994) and Hughes and Styles (1989) are exceptional among recent contributions in that they also provide practical guidelines how to avoid invasions from agroforestry trees.

Problems with invasions in agroforestry are not nearly as well reported in the international literature as is the case for invasions associated with commercial forestry (see reviews in Richardson 1998a, 1998b, 1998c), although several recent publications on agroforestry list low invasiveness as a selection criterion for agroforestry trees (Young 1997; Elevitch and Wilkinson 2001), warn against uncritical distribution of seed lots (Huxley 1999), or mention reported invasiveness in species descriptions (Salim et al. 1998). However, detailed accounts of invasiveness for a range of tree species, including agroforestry trees, have only recently become available (Binggeli et al. 1998; CABI 2000).

The fact that invasions have received little attention in the agroforestry literature may be because invasions are simply not perceived or reported to the same extent in agroforestry as they are in forestry. It may also be because the ecosystems that are affected by agroforestry often are degraded sites where concerns regarding impacts of invading plants are not high priorities. However, where agroforestry is practiced in buffer zones around protected areas (Chapters 17 and 18, this volume), invasiveness of agroforestry trees could negate any advantages gained from the provision of alternative timber and fuel sources, buffering, and interconnecting forest fragments (see Chapters 2 and 3, this volume).

Despite the lack of a complete global picture of the dimensions of plant invasions associated with agroforestry, it seems prudent to make a preliminary assessment of the situation by reviewing what information exists and drawing insights from advances in the understanding of plant invasions in general.

Advances in Plant Invasion Ecology Applied to Agroforestry

We begin by discussing recent advances in the understanding of the ecology of alien plant invasions in general. Biological invasions are notoriously idiosyncratic, leading some authors to suggest that attempts to predict the outcomes of introduction are futile. Nonetheless, there has been much progress over the past few decades toward developing a toolbox for understanding (Rejmánek et al. 2004) and managing (Wittenberg and Cock 2001) plant invasions. Rejmánek et al. (2003) discuss a number of robust generalizations that have emerged from recent research on plant invasions (Appendix 15.1). Some of the points in Appendix 15.1 are interrelated, some relate to complicated processes that are beyond the scope of this chapter, and some relate primarily or specifically to nonwoody plants. However, several points have important practical implications for actual or potential invasions of agroforestry trees and shrubs and ways of managing such invasions.

Invasion Success Is Positively Correlated with Propagule Pressure and Time Since Introduction

One robust generalization is that problems with invasions increase as the size of the propagule pool and the time since introduction increase. For agroforestry this means that we should look at the oldest and largest plantings when seeking generalizations. Importantly, the lack of invasions from recent (perhaps experimental) plantings does not necessarily mean that these species will not invade at these sites in the future, or when planted on a larger scale. Many mistakes are made in assessing the invasiveness of species after even a few decades of cultivation in new habitats. The passage of time changes many parameters such as the likelihood of favorable chance events, the likelihood of encountering mutualistic symbionts, genetic adaptation, and natural population growth. Very large numbers of propagules can result in successful invasions, even if the environment is suboptimal for establishment of the species. This is the result of a mass effect whereby potential establishment sites are swamped, allowing some propagules to capitalize on rare facilitating events.

Some Species Are Inherently Better Invaders Than Others

Recent syntheses of plant invasion ecology and regional and global compendia provide us with global lists of the most invasive taxa. Many interesting and useful generalizations can be drawn from such lists. For example, there is clear evidence that if a species is highly invasive in one part of the world, there is a high risk of it replicating its invasiveness in similar environments elsewhere. Also, some plant taxa are much more likely to invade when introduced to new habitats than others. Such empirical evidence is very useful for management. For example, it can be used to compile "black lists" of species known to be invasive, which either should not be used in new agroforestry operations or warrant special management attention. The use of "white lists" (safe species) is much more problematic because time lags, introduction history and many other factors, make it difficult to know when any species can confidently be considered safe (Rejmánek et al. 2003).

Genetic Change Caused by Introduction and Cultivation History Can Favor Invasiveness

Changes in the genetic makeup of introduced species can have a marked effect on their ability to invade. This may be as a result of the evolution of landraces that are more suited to local conditions than original introductions, increased genetic diversity as a result of the introduction of new genotypes, spontaneous hybridization in situ (e.g., *Prosopis* taxa in South Africa, Poynton 1990; *Leucaena* taxa, Hughes 1998), or human-mediated breeding programs aimed at genetic improvement. Spontaneous interspecific hybridization is important for the evolution of invasiveness in plants (Ellstrand and Schierenbeck 2000). Hybridization can change the rules for an alien organism and may enhance its ability to become established and invasive through the greater vitality of the hybrids compared with the parent species.

Prolific Seed Production Spells Trouble

Most invasive agroforestry species regenerate from seeds. Various aspects of seed biology are important determinants of invasiveness (Rejmánek et al. 2003). Heavy seed production in the absence of natural enemies is a crucial factor in many plant invasions. Very large seed numbers can swamp regeneration microsites, thus reducing the potential effect of biotic (and even abiotic) resistance (Rejmánek et al. 2003). Heavy seed production also affects dispersal in several ways. More seeds usually result in more offspring further from parent plants. Importantly, very large seed numbers greatly increase the probability of seeds traveling great distances (many orders of magnitude further than the mode for all seeds) and establishing satellite populations. Such isolated populations are disproportionately important in initiating invasions (Higgins and Richardson 1999) and greatly complicate the task of containment. Biological control using seed-attacking insects has great potential to reduce seed production of desirable (but invasive) agroforestry species without affecting other features of the plant. For example, much progress has been made in South Africa with biocontrol of *Acacia* spp. (Dennill et al. 1999) and *Prosopis* spp. (Impson et al. 1999; see also Richardson 1998a).

The rapid onset of seed production, a key criterion for the mass production of planting material, also confers invasiveness in many situations. Early maturity in plants usually is associated with other traits that confer colonizing ability (Richardson et al. 1990; Rejmánek and Richardson 1996). It is difficult to select for one trait without getting the "whole package" (Richardson 1998c).

Mutualisms Are Critically Important, and Reshuffling the World's Biota Is Making Ecosystems More Open to Invasion by More Species

Many invasions depend on mutualistic interactions between the introduced plant species and other organisms in the new habitat. Among the most important of these are animal-mediated pollination and seed dispersal and interactions between plant roots and mycorrhizal fungi and nitrogen-fixing bacteria (Richardson et al. 2000a). Generalist vertebrate seed dispersers such as cattle, goats, and sheep often are a component of agroforestry systems and provide a reliable mechanism for seed movement in the new habitat. Added to this is the fact that propagules of many agroforestry trees are widely disseminated by humans. These factors contribute to enhanced long-distance dispersal and the establishment of new foci for invasion. Potential barriers to establishment (and invasion beyond planting sites) are overcome for many agroforestry trees and shrubs when appropriate mycorrhizal symbionts and bacteria are introduced. Such inoculations enable the alien agroforestry species to grow productively in the new habitat and also radically enhance the suitability of surrounding areas for establishment and invasion by the alien species (Richardson et al. 2000a).

Potential Impacts of Invaders Often Are Related to the Functions and Services That Make These Species Desirable Subjects for Agroforestry

Alien species used in agroforestry are selected for the new functions and services that they bring to the system, functions and services that cannot be provided (as well) by native species. It is often exactly these functions and services (e.g., rapid biomass accumulation, nitrogen fixation) that cause harmful impacts when these species invade beyond sites intended for agroforestry. Such species have been called ecosystem engineers (Crooks 2002).

Experimentation with Many Species Worldwide Ensures Better Species-Site Matching Than in the Past

Improved communication between agroforesters in many parts of the world has resulted in the rapid and widespread dissemination of news of highly successful agroforestry species (e.g., the many species of "miracle trees"). Such information, based on the natural experiment of the planting of hundreds of species across the world is providing empirical evidence on species-site matching. Rather than needing to experiment with a large number of potential species, agroforesters are able to select from a small number of species with a very high chance of success in their area. Species selection following this process, in many cases, is also selecting for invasiveness.

Many Facets of Global Change Alter Ecosystems and Trigger, Facilitate, or Sustain Invasions

The many facets of global change (e.g., global warming, elevated CO_2 concentrations, and altered nutrient-cycling and disturbance regimes) are widely expected to greatly exacerbate the nature and magnitude of problems with biological invasions in the next few decades (Mooney and Hobbs 2000; see also Chapter 20, this volume).

Trees Typically Used in Agroforestry: Current Levels of Invasiveness, Perceptions, and Approaches

Detailed monographs of a number of key agroforestry species, several known as highly invasive, have been published recently (e.g., *Acacia karroo,* Barnes et al. 1996; *Acacia seyal,* Hall and McAllan 1993; *Balanites aegyptiaca,* Hall and Walker 1991; *Calliandra calothyrsus,* Chamberlain 2001; *Cordia alliodora,* Greaves and McCarter 1990; *Gliricidia sepium,* Stewart et al. 1996; *Leucaena* spp., Hughes 1998; *Parkia biglobosa,* Hall et al. 1997; *Prosopis* spp., Pasiecznik et al. 2001; *Vitellaria paradoxa,* Hall et al. 1996). Where appropriate (i.e., *A. karroo, C. calothyrsus, Prosopis* spp., *Leucaena* spp.), these monographs include sections on the introduction, invasive potential, and impacts of the species in the introduced range.

Here we review the experience with invasiveness for some taxa of trees and shrubs that are commonly used in agroforestry. We have divided the taxa into groups corresponding to their typical functions in agroforestry land uses. This is because when aiming to substitute noninvasive taxa for invasive (or potentially invasive) taxa, one needs to find functionally equivalent rather than taxonomically related species.

Fast-Growing, Nitrogen-Fixing Legume Trees

This group includes a large number of pioneer species that are commonly used in agroforestry because of their ability to grow on nitrogen-deficient sites where they improve fertility with their litter and prunings, to produce large amounts of fuelwood, and to provide protein-rich foliage and pods. The many uses of such trees make them typical multipurpose trees that are used in reforestation of degraded land, improved fallows, contour hedgerows, and silvopastoral systems. Many of these species cast a light shade and resprout readily even after severe crown pruning, which makes them ideal shade trees for tree crops such as coffee and cocoa.

The best-known example of this group is *Leucaena leucocephala,* a small tree from Central America that has been introduced to most parts of the tropics, starting more than 400 years ago when the Spanish brought it to the Philippines (Binggeli et al. 1998). It has been used as a shade tree for coffee, cocoa, and tea, for windbreaks and firebreaks, and for many other purposes. Since 1983 the species has been attacked by the psyllid insect *Heteropsylla cubana,* which causes defoliation and tree death especially in dry regions. This has inspired the search for alternatives, including other *Leucaena* species. Other Latin American legume trees used extensively outside their home range include *Gliricidia sepium* and *Calliandra calothyrsus. G. sepium* often is used for live fences, as cocoa shade, and for many of the same purposes as *L. leucocephala. C. calothyrsus* was brought from Guatemala to Java in 1936 as a potential shade tree in coffee but was then mainly used by villagers for fuelwood plantations, as fodder plant and bee pasture, and as a planted fallow tree for the regeneration of agricultural soils (NRC 1983a). More recently, *C. calothyrsus* has also been used in short-rotation fallows and as a fodder tree in East Africa. In Cameroon it is used in rotational tree fallow systems where *L. leucocephala* is no longer used because of its invasiveness (Kanmegne and Degrange 2002).

Leucaena leucocephala is highly invasive and has been recorded as a weed in West, East, and South Africa, India, Southeast Asia, Australia, and several Pacific, Indian Ocean, and Caribbean islands (Binggeli et al. 1998; Hughes and Jones 1998; Meyer 2000; Henderson 2001; Randall 2002). It invades open and disturbed habitats such as roadsides and abandoned fields and pastures, where it may form dense, monotypic stands, currently covering about 5 million ha worldwide (Binggeli et al. 1998). The species is very common in the roadside vegetation in the forest zone of the Côte d'Ivoire, where it was used as shade tree in coffee (R. Peltier, pers. comm., 2001). It replaces open forest in Hawaii and threatens endemic species on several oceanic islands (Binggeli et al. 1998). It is not known to invade undisturbed closed forests (Hughes and Jones 1998) but may invade disturbed dry forest (Binggeli et al. 1998). In a fallow improvement trial with several introduced legume tree species on a degraded soil in the Côte d'Ivoire, *L. leucocephala* had the densest understory of all species under consideration, consisting almost entirely of its own regeneration (Schroth et al. 1996). The abundant regeneration of this tree species was recognized as a problem when it was used as coffee and tea shade in Indonesia and inspired research into sterile hybrids (Dijkman 1950; Hughes and Jones 1998).

Other widely used species from this group have caused fewer problems. For *Leucaena diversifolia,* the second most widely planted species in this genus, this may simply be a consequence of the shorter time of extensive plantings and its more limited use. The two species share the same weedy traits (precocious flowering and fruiting, abundant seed production, self-fertility, hard seed coat, and ability to resprout after fire or cutting; CABI 2000; Hughes 1998), suggesting that new introductions generally should be avoided. In contrast, *C. calothyrsus* has been used in agroforestry for more than half a century, including for planting around state forest land in Java (NRC 1983a), which would be an excellent starting point for invading these forests once they have been logged. Yet it has rarely been reported as invasive (http://www.hear.org/pier/cacal.htm), possibly because of its low seed production (CABI 2000). However, careful observation of the species in areas where it has been introduced more recently is needed. Similarly, despite its widespread use in agroforestry throughout the tropics, *Gliricidia sepium* has also not caused widespread problems as an invader, except in Jamaica (Holm et al. 1979). It is also known to be naturalized on Koolan Island off the tropical Western Australian coast (Keighery et al. 1995). It is listed as potentially weedy in the Pacific Islands, where it was recently introduced (Thaman et al. 2000). Sources collated by Randall (2002) list *G. sepium* as "weed," "quarantine weed," "naturalized," "garden escape," "environmental weed," and "cultivation escape," suggesting its potential to cause bigger problems in the future. Much work has been done on genetic improvement of *G. sepium* (e.g., Chamberlain and Pottinger 1995), and new genotypes may well prove to be more invasive.

Another group of fast-growing, nitrogen-fixing agroforestry trees with somewhat different properties is the Australasian acacias, especially *Acacia auriculiformis* and *A. mangium.* Because of their ability to grow and produce large amounts of fuelwood even on severely degraded soils and to colonize grassland, *A. auriculiformis* and to a lesser extent *A. mangium* have been introduced to many tropical countries. The use of these species in agroforestry is recent and not yet common but is likely to increase in the future because of their exceptional characteristics. Both species are listed in Randall's (2002) *Global Compendium of Weeds* and have the potential to become more invasive in the future (CABI 2000; http://www.hear.org/pier/acman.htm; http://www.hear.org/pier/acaur.htm). *A. mangium* seeds and regenerates prolifically, although disturbance of the understory, as by fire, usually is necessary for large-scale natural regeneration (NRC 1983b). Several closely related *Acacia* species are highly invasive in southern Africa, namely, *A. cyclops, A. longifolia, A. melanoxylon, A. mearnsii, A. pycnantha,* and *A. saligna* (Richardson et al. 1997; Henderson 2001). Randall (2002) lists 288 *Acacia* species, about a fourth of this large genus, with the status of casual alien, "quarantine weed," or worse.

Trees for Dry Zones

In semiarid regions, cutting and lopping of trees for timber, fuelwood, and fodder in combination with browsing, recurrent fires, and a harsh climate have caused widespread degradation of vegetation and soils. Increasing tree cover in such areas has been the objective of many development projects. Because tree growth is generally slow and mortality high under these conditions, selecting site-adapted species is particularly important. Promising species such as *Acacia nilotica, Azadirachta indica,* and *Prosopis* spp., (neem) have been introduced into many countries outside their native home range (Salim et al. 1998). Because of their outstanding growth characteristics, they have often proved superior competitors to the native vegetation and become invasive.

Acacia nilotica, native to India, Pakistan, and much of Africa, was introduced to western Queensland, Australia, as a shade and fodder species in the 1920s and initially caused no problems as an invader. It first became naturalized along creeks and boredrains and became widespread and invasive after a series of years with above-average rainfall in the 1970s. It now forms stands of several thousand shrubs per hectare in pastures in coastal areas (Carter 1994; Tiver et al. 2001; van Klinken and Campbell 2001).

Azadirachta indica is native to Southeast Asia and India but has been widely planted outside its range. It is known to be invasive in Ghana (http://www.green.ox.ac.uk/cnrd/jo.htm#darwin), spreads from rural plantings into undisturbed bush in northern Australia (A. A. Mitchell, pers. comm., 2002), and is also listed as a potential environmental weed in Australia (Cshurhes and Edwards 1998). Although various sources list *A. indica* as "weed," "naturalized," "garden escape," or "environmental weed" (Randall 2002).

The neotropical *Prosopis juliflora* and closely related species have been widely used in the dry tropics to halt desertification because they tolerate low rainfall, great heat, and poor and saline soils and because of their ability to stabilize sand dunes (e.g., in Sudan and Pakistan) and enrich the soil through their nitrogen fixation. Other products include good-quality fuelwood and charcoal, pods as fodder and food, and seed gum. Because of the low palatability of its foliage, *P. juliflora* is suitable for use as a live fence (CABI 2000). It has been widely introduced throughout the dry tropics and has spread over large tracts of Africa, Asia, and South America (Hulme n.d.; Jadhav et al. 1993; Sharma and Dakshini 1998; Tiwari and Rahmani 1999). Its invasive potential has long been known but has until recently gained little attention or, in very degraded areas, even been seen as a bonus. Referring to Africa, Baumer

(1990, p. 170) stated that "one would be only too happy in certain very degraded, not to say denuded, regions to find an invasive plant with as many qualities as *Prosopis,*"a view that reflects particularly well the ambivalence of the use of aggressive colonizers in areas badly in need of tree cover (see also Coppen 1995; El Fadl 1997). These authors also argued that the spread of *P. juliflora* must be checked in areas that are not degraded and suggested that this could be achieved through good management but did not provide concrete guidelines.

Although the deleterious impacts of root competition and allelopathy of *P. juliflora* in agricultural areas have been noted earlier (Baumer 1990; Coppen 1995), the environmental and human impacts of invasions by this species have only recently gained more attention (e.g., review by Pasiecznik et al. 2001). In 1999, an Ethiopian workshop on agricultural weeds concluded, after much debate, that the species was on balance detrimental to the environment and should be eradicated (Anonymous 1999). In neighboring Kenya, after *P. juliflora* introduction in the early 1980s and subsequent rapid spread, it has been reported that toxicity and even death have occurred in livestock after pod ingestion. The tree locust (*Anacridium melanorhodon arabafrum*), a well-known African pest, feeds on *P. juliflora,* and it is feared that this insect, hitherto not a problem in the Lake Turkana region, might become established in this part of Kenya (Anonymous 1997). In northeastern Brazil, *P. juliflora* has spread from managed agricultural systems into arid shrublands (caatinga) rich in endemic species, where its impact on biodiversity is viewed as highly detrimental (Hulme n.d.). In Gujarat, India, *P. juliflora* is viewed as negatively affecting pastures, cattle health, and water resources and is viewed as a threat to number of bird and mammal species (Jhala 1993). However, it does play a role in erosion control and provides people with a source of income from charcoal, pods, and honey. It is therefore thought that the tree should be contained rather than eradicated (Tiwari and Rahmani 1999). A detailed study by Gold (1999) of an Indian rural village community confronted with deforestation, where an aid program had been established in 1993 to plant *P. juliflora* on the hilly wastelands, revealed that the species had become the only source of fuelwood. However, local people also identified a number of significant drawbacks: it colonizes agricultural land and is hard to remove, its thorns cause dangerous infections and play havoc with bicycle tires, the leaves are unappealing to goats, and no grass or crops grow in its shade. Consequently, local people considered *P. juliflora* to have fewer uses than native trees.

The genus *Prosopis* has an interesting history in South Africa. Several species have been widely used as amenity trees, mainly for livestock fodder and shade, in the arid parts of the country. After the spontaneous hybridization of several taxa (notably *P. glandulosa* var. *torreyana* and *P. velutina*), *Prosopis* spp. rapidly spread over huge areas, making large tracts of rangeland unproductive (Harding and Bate 1991). There is an ongoing debate on whether *Prosopis* is a friend or foe in South Africa, but opinions are converging on the latter view. The national "Working for Water Programme" (http://www-dwaf.pwv.gov.za/wfw) has spearheaded an innovative management program for invasive *Prosopis* spp., involving mechanical and chemical control, the management of livestock, and biological control using seed-attacking insects (Richardson 1998a). *Prosopis* species are also among the "weeds of national significance" in Australia and cause serious impacts over some 800,000 ha, mainly in northern Australia. A strategic plan for managing these invasions aims to remove the current stands and to prevent impacts by coordinating and maintaining management at a national level, containing all core infestations and subjecting them to sustained management aimed at eventually eradicating them, removing all isolated and scattered stands, and preventing further spread (Agriculture & Resource Management Council of Australia and New Zealand 2001).

Nonlegume Service Trees

The Latin American pioneer tree *Cecropia peltata,* which forms a complex with *Cecropia pachystachya* and *C. concolor,* is a particularly interesting case because it shows that an alien agroforestry tree may initially appear harmless but may become invasive once human activities or climate change have created more favorable conditions for its spread. It was introduced to the Côte d'Ivoire in 1910 as a shade tree in coffee plantations and spread very slowly in the first six decades. Subsequent large-scale destruction of the forest cover (see Chapter 6, this volume) created the open, disturbed conditions necessary for its rapid spread in competition with native pioneer species (Binggeli et al. 1998). The species has also become invasive in other places in Africa, Southeast Asia (Binggeli et al. 1998), French Polynesia (Meyer 2000), and Hawaii (http://www.hear.org/pier3/cepel.htm). A related species, *Cecropia obtusifolia,* is highly invasive in the Cook Islands, where it is also widely used as a shade species in coffee plantations (Meyer 2000).

Fast-Growing Timber Trees

This group includes a number of tree species whose main characteristic is their fast growth. Such trees are in high demand in deforested regions for the production of fuelwood, poles, and as windbreaks; use as shade trees is less common. The genus *Eucalyptus* includes a number of fast-growing tree species that are commonly used not only in plantation forestry but also in agroforestry in both dry and humid tropical regions. *Eucalyptus camaldulensis* and *E. tereticornis* are planted as windbreaks in dry regions (CABI 2000), and *E. globulus* and several other *Eucalyptus* spp. are commonly planted around cultivated fields and in farm wood lots in the deforested Ethiopian highlands (Demel Teketay

2000) and are also used in many other tropical countries (CABI 2000). In humid tropical Costa Rica, *E. deglupta* is increasingly used as coffee shade because of its fast growth, homogeneous light shade, and low pruning needs compared with the traditional legume shade trees (Tavares et al. 1999). *Eucalyptus* spp. also were promoted for fuelwood plantations in buffer zones around protected forests in Uganda and Burundi in the 1980s, although the respective projects later shifted toward the use of local tree species (van Orsdol 1987).

Eucalypts are naturalized or (usually marginally) invasive in many parts of the world. Randall (2002) lists no fewer than 67 *Eucalyptus* species that have been listed as "weed," "sleeper weed," "quarantine weed," "noxious weed," "naturalized," "native weed," "garden escape," "environmental weed," "cultivation escape," or "casual alien" in various parts of the world. *Eucalyptus* species given four or more status categories in Randall's (2002) compendium, and therefore possibly the most widely naturalized, are *E. botryoides, E. camaldulensis, E. cladocalyx, E. conferruminata, E. globulus, E. grandis, E. lehmannii, E. leucoxylon, E. maculata, E. paniculata, E. polyanthemos, E. saligna,* and *E. sideroxylon.* In South Africa, *E. camaldulensis, E. cladocalyx, E. diversicolor, E. grandis, E. lehmannii, E. paniculata,* and *E. sideroxylon* are considered invasive (Henderson 2001), although only *E. camaldulensis* and *E. lehmannii* are unquestionably "invasive" as defined earlier (Forsyth et al. 2004). Despite their appearance in many weed lists, eucalypts have fared poorly as invaders when compared with other tree genera that have been planted to a similar extent in many parts of the world. *Pinus,* the obvious comparison (although not widely used in agroforestry), has been orders of magnitude more successful. For example, Richardson and Higgins (1998) list 19 *Pinus* species that are clearly invasive (*sensu* Richardson et al. 2000b) in the Southern Hemisphere. Rejmánek et al. (2004), in reviewing invasiveness in *Eucalyptus* (or the lack thereof), concluded that propagule pressure (large seed pools) explains much more of the variance in observed invasiveness in eucalypt taxa than any known combination of ecological factors. This suggests that the risk of invasiveness is much smaller when eucalypts are used in windbreaks or other agroforestry practices involving small tree numbers per hectare than when they are used in plantation forestry. The use of eucalypts as shade trees in coffee over large areas represents an intermediate case. Further work is needed to quantify this relationship and the invasion ecology of *Eucalyptus* in general.

Casuarina equisetifolia, an actinorhizal tree species native to Australasia, has been widely planted in Africa, South and Central America, and the Caribbean. Its nitrogen-fixing ability allows it to grow on very poor sandy soils, and it is often used for sand dune stabilization and in shelterbelts, especially in coastal areas. It readily invades disturbed vegetation in many parts of the world. It has spread in Hawaii and has invaded the Everglades National

Park in Florida, where its roots also interfere with the nesting of sea turtles on foreshore dunes (Geary 1983; Binggeli et al. 1998). This species, and *C. cunninghamiana,* are also invasive over large parts of the eastern half of South Africa, especially along the eastern seaboard (Henderson 2001).

High-Value Timber Trees

Several high-value timber species, which are used in agroforestry in their native ranges, have become invasive in parts of the tropics to which they had been introduced for forestry plantations. The planting of high-value timber species on farms is likely to increase in the near future when the supply of such timbers from natural forests ceases and could in fact be a way of simultaneously increasing farm incomes and reducing pressure on remaining forests. In future agroforestry programs, experience with invasive plantation species must be taken into account to avoid introducing potentially invasive species into sensitive areas, such as buffer zones. For example, *Swietenia macrophylla* (mahogany, Meliaceae), is planted by farmers in association with fruit trees both in its native Amazonia and in Indonesia, where it is alien (Michon and de Foresta *1995);* invasion by this species of native forests especially after disturbance (Commonwealth Agricultural Bureau International 2000) has been observed in Sri Lanka, Asia, and the Pacific Islands. Cordia alliodora, a common local shade tree in coffee and cocoa plantations in Latin America (Beer et al. 1998), has been widely planted in Africa for timber production (Richardson 1998a). It was planted in Vanuatu to provide timber; however, regular cyclones caused havoc with the trees and subsequent heavy cattle grazing enhanced their regeneration and spread, thus reducing the grazing potential of the land (Tolfts 1997; Meyer 2000).

Fruit Trees

Fruit trees are important components of agroforestry systems such as homegardens and mixed tree crop plantations and often provide an important basis for farmers' subsistence and income. As with other agricultural crops, the use of alien species is common, and the invasion of native ecosystems has been reported for a few species. The possibilities of exchanging an alien for a native species or an invasive alien for a noninvasive alien are much more limited for fruit trees than for shade or soil-improving trees because of the restrictions on species selection imposed by consumption preferences and local markets for fruits.

The most notorious case of an alien fruit tree becoming a weed is guava (*Psidium guajava*). This small tree, native to the American tropics, has been introduced throughout the tropics since colonial times. It is a pasture weed in

Central America and a serious weed in arable plantation and pastureland on the Fiji Islands. The seeds are spread by cattle, making it difficult to eradicate from pastures. The impact of introduced guava on the native vegetation has been best documented on the Galapagos Islands, where it invades disturbed forest and outcompetes endemic plant species (BOSTID 1983; Binggeli et al. 1998). This species is also highly invasive in natural vegetation in eastern South Africa (Richardson et al. 1997; Henderson 2001). A related species, *Psidium cattleianum,* is one of the worst invaders in many islands in the Indian Ocean (notably on La Réunion; Macdonald et al. 1991) and the Pacific (Meyer 2000).

Another example is *Passiflora mollissima* (banana passion fruit or curuba), a woody vine up to 20 m in length originating from the Andes that has been cultivated for its fruits and as an ornamental in several tropical countries and has become invasive in Hawaii, New Zealand, and South and East Africa. In Hawaii it has spread into native forest, scrub vegetation, pastures, forestry plantations, and lava flows, suppressing tree regeneration and killing trees through shading, thereby reducing species richness. The prolific fruit production increases populations of feral pigs. The species is also naturalized in South African forests and grows at forest edges and in clearings in East Africa (Binggeli et al. 1998). In Paraguay, *Citrus* species (*C. aurantium, C. sinensis,* and intermediate types) readily spread into undisturbed forest and become a characteristic feature of their understory, a process that is favored by grove abandonment (Gade 1976).

Invasive Agroforestry Trees: Scenarios and Management Options

Effective management of invasive agroforestry trees demands action at global, regional, national, and local scales. The recent *Global Strategy on Invasive Alien Species* (McNeely et al. 2001) provides a good starting point for global attention to the problem. A global plan should build management capacity; build research capacity; promote information sharing; develop economic policies and tools; strengthen national, regional, and international legal and institutional frameworks; institute a system of environmental risk analysis; build public awareness; prepare national strategies and plans; build alien species into global change initiatives; and promote international cooperation.

Various options are available for reducing actual or potential impacts of invasive agroforestry trees in different situations. The conceptualization of the naturalization and invasion process (Figure 15.1) provides a template for planning interventions to strengthen different barriers to prevent widespread invasion and impacts. For example, excluding known invasive alien species (or, ideally, all alien species) from agroforestry projects strengthens the geographic barrier; combinations of burning, grazing, and weeding can strengthen the local environmental barrier and limit regeneration of invasive species; and management of livestock and other seed dispersal agents can strengthen reproductive and dispersal barriers, as could genetic engineering to produce sterile trees, although the usefulness of this approach for agroforestry has not yet been explored. Ledgard and Langer (1999) provide an excellent example of practical ways to reduce invasive spread from forestry plantations in New Zealand. Similar guidelines could be produced for different agroforestry land uses. In this section we propose some guidelines, based on the information reviewed in this chapter, for reducing or mitigating problems associated with invasions of agroforestry trees.

Wherever Possible, Use Local Tree Species in Agroforestry

An obvious way to avoid risks of invasiveness is to use only native species. Avoiding nonnative species is most feasible in the case of service trees (e.g., species for shade or soil conservation), where several alternative species may be available in a region, though perhaps not with identical properties. Trees grown for commercial products with established markets are much more difficult to substitute, but the introduction of invasive species to new regions or their promotion in sensitive areas such as agroforestry buffer zones should nevertheless be avoided. Where agroforestry is intended also to serve conservation purposes, as in buffer zones or biodiversity-friendly coffee or cocoa production systems, native tree species also have the advantage of creating habitat for native fauna. In mainly deforested landscapes, the promotion of native species will contribute to the in situ conservation of local tree germplasm (see Chapter 12, this volume). Furthermore, native species provide goods and services with which the population is familiar (e.g., medicinal uses).

The feasibility of this approach depends on the availability of species in the native flora that are suitable for the intended uses, the ease of obtaining seeds or vegetative propagation material, knowledge of site needs, growth rates, conditions for germination, inoculation requirements, and establishment and management methods. Working with little-known species is clearly a risk and may delay the generation of demonstrable results. These difficulties decrease as more information on local fruit, timber, and service trees becomes available from national and international research centers (Salim et al. 1998; CABI 2000). In many cases, however, a local species that is as effective for a given purpose as the best alien species may simply not be available or may remain to be identified. In such cases, using the second- or third-best (local) choice may mean sacrificing farmers' interests to avoid the risk of invasiveness. However, it should also be mentioned that the focus on very fast-growing "miracle trees" in agroforestry has often led to problems of competition with crops; such problems may be less severe when local tree species with intermediate growth rates are used. This conflict of interest in searching for the best-performing species while trying to avoid introduced species can be particularly severe in strongly degraded, arid environments, where species with outstanding growth characteristics such as *Prosopis* spp. have often been introduced and become invasive. Where agroforestry plantings are intended to reduce pressure on overused native ecosystems, especially in arid regions, a fast-growing but non-invasive alien tree species could be more beneficial for biodiversity than a native species that produces timber, fuelwood, and other tree products at lower rates. Objective estimates of the risks of invasiveness for potential species are clearly needed for this approach.

Subject Species Selection to Formal Cost-Benefit Analysis and Environmental Impact Assessment

Potential costs associated with the spread of agroforestry species beyond sites set aside for planting and the associated damage to natural ecosystems (including a wide range of ecosystem services) must be assessed before an agroforestry project is initiated. The polluter-pays principle is being advocated as an element of the solution to the problem of invasive forestry tree species in South Africa (Richardson 1998a), and it should be explored for agroforestry. But who is the polluter who pays? The small farmer who accepted the introduced tree? The research institution, perhaps a foreign university, whose 3-year project ended long before the species became invasive? The seed bank that responded to the request of a local research station and sent *Leucaena* seeds? The principle is clearly easier to apply with a forestry company establishing commercial plantations than with typically decentralized, small-scale, and noncommercial agroforestry projects.

Continued use of known invasive species in areas where they are already planted and new plantings of such species should be done with due cognizance of potential harmful effects of invasions. In sensitive areas such as buffer zones of protected areas, conservation payments or access to preferential markets for biodiversity-friendly products may be the best way to persuade farmers to do without economically attractive but potentially invasive alien species.

Establish Criteria for Rational Risk Assessment for Agroforestry Worldwide

Apart from the agroforestry species widely known to be invasive, there are many other species that are likely to become invasive in the future. Research is needed to establish criteria for the objective assessment of the potential risk of any alien species becoming invasive at a given locality. Global black lists have limited value because they are generally too restrictive; in fact, there is reason to tag even some well-known invasive species as safe for use in certain environments or under certain conditions. For example, some species grow well but do not produce fruits in certain climates, such as *Gliricidia sepium* in climates without a well-defined dry season. Some species may show poor growth outside agricultural areas because of low adaptation to infertile soil or may need fire for regeneration. As with other predictions of invasiveness, it should be noted that conditions (e.g., nutrient conditions, climate, and fire frequency) at a site change. For this reason, assessments must be time- and site-specific.

Provide Easy Access to Up-to-Date, Objective Information on Invasiveness of Agroforestry Species

Many species that are used in agroforestry are widely known to be invasive in all or most sites where they are used. Such information already resides in widely available databases such as International Centre for Research in Agroforestry's Agroforestree Database (Salim et al. 1998), CABI's[1] *Forestry Compendium* (CABI 2000), and R. P. Randall's (2002) *Global Compendium of Weeds.* Further efforts are needed to ensure that such databases are kept up to date and that assessments are based on objective criteria.

Include Explicit Considerations of Invasiveness in Standard Assessments for Species-Site Matching

Detailed assessments of the suitability of particular species for use in agroforestry (e.g., Durr 2001 for *Samanea saman*), as a matter of course, should include objective assessments of the potential for the species to become invasive.

Incorporate Considerations Relating to Invasion in Standard Management Protocols

For example, pruning trees to prevent them from producing fruits is done in many agroforestry situations and could possibly be a practical prevention strategy in some cases. However, relying on this strategy is risky because trees may remain unpruned in some areas or years, and the strategy would fail when an area is abandoned temporally or permanently. Where tree felling for wood collection is legally restricted (e.g., parks), restrictions could be relaxed to allow felling of invasive alien species (J. Healey, pers. comm., 2001).[2]

Conclusions

Our knowledge of plant invasions that are the direct result of agroforestry is fragmentary. We know that some tree and shrub species that are (or have until recently been) widely used in agroforestry are among the most widespread and damaging of plant invaders. We also know that our knowledge base is changing rapidly. Some species that were deemed safe based on available information even a decade ago are now known to be invasive. The natural experiment involving the plantings of thousands of species in many types of environment is ongoing. Guidelines for reducing the problems, without excluding every potential agroforestry species, must be reviewed at regular intervals. A thorough global survey of problems and the perspectives of interested and affected parties is urgently needed. Such a global perspective is essential for rational planning in countries or regions.

Effective management of plant invasions at a site entails the integration of approaches for dealing with species that have already spread over large areas and for assessing other alien species already present in an area but perhaps not showing signs of invasion. Also critically important is the need to screen new introductions to identify species that have a high risk of invading if introduced.

Biotechnology has been proposed as a way of reducing problems of invasiveness by controlling flowering and thereby reducing or eliminating seed production in forestry plantations (Strauss et al. 2001; Meilan et al. 2001). The use of this approach to agroforestry trees warrants careful consideration, taking into account problems of both feasibility (small-scale, often noncommercial agroforestry with many different tree species as opposed to the large-scale use of a few species in commercial plantation forestry) and desirability (e.g., dependency of farmers on external seed suppliers, poorly understood environmental risks of genetic engineering).

Because the invasion-related problems faced by agroforestry are not unique, it seems logical to strive for coordinated efforts in the various plant-related enterprises that rely heavily on alien species. Efforts in commercial forestry have already been mentioned (Richardson 1998a, 1998b, 1998c; Rouget et al. 2002). Attempts are also being made to understand the various pathways affecting invasions as a result of aquaculture (Naylor et al. 2001) and horticulture (Reichard and White 2001), both of which also rely heavily on alien species. Agroforestry is lagging behind, and a clear strategy for dealing with the increasing problem of invasive species is urgently needed.

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Appendix 15.1

This is a summary of generalizations regarding alien plant invasions, based on information reviewed in Rejmánek et al. (2004). Not all these points apply equally to all types of plants or in all situations.

1. Which taxa invade?
   - 1.1. Stochastic approach
     - 1.1.1. The probability of invasion success increases with initial population size and the number of introduction attempts (propagule pressure).
     - 1.1.2. Long residence time improves the chances of invasion.
     - 1.1.3. Many or most plant invasions are preceded by a lag phase that may last many decades.
   - 1.2. Empirical, taxon-specific approach
     - 1.2.1. If a species is invasive anywhere in the world, there is a good chance that it will invade similar habitats in other parts of the world.
     - 1.2.2. Among invasive plants, some families (Amaranthaceae, Brassicaceae, Fabaceae, Hydrocharitaceae, Papaveraceae, Pinaceae, Poaceae, and Polygonaceae) are significantly overrepresented.
   - 1.3. The role of biological characters
     - 1.3.1. Fitness homeostasis (maintenance of fitness over a range of environmental conditions) is an important determinant of invasiveness.
     - 1.3.2. Genetic change can facilitate invasions, but many species have sufficient phenotypic plasticity to exploit new environments.
     - 1.3.3. Small genome size (SGS) has value as an indicator of invasiveness in closely related taxa (SGS seems to be a result of selection for short minimum generation time, and because it is also associated with small seed size, high leaf area ratio, and high relative growth rate of seedlings in congeners, it may be an ultimate determinant or at least an indicator of invasiveness).
     - 1.3.4. Several characters linked to reproduction and dispersal are key indicators of invasiveness (e.g., simple or flexible breeding systems, small seed mass, short juvenile period, short intervals between large seed crops, long flowering and fruiting periods).
     - 1.3.5. Seed dispersal by vertebrates is implicated in many plant invasions.
     - 1.3.6. Low relative growth rate of seedlings and low specific leaf area (the ratio of leaf area to leaf dry mass) are good indicators of low plant invasiveness in many environments.
     - 1.3.7. Large native range is an indicator of potential invasiveness.
     - 1.3.8. Vegetative reproduction is responsible for many plant invasions.
     - 1.3.9. Alien taxa are more likely to invade a given area if native members of the same genera (and family) are absent, partly because many herbivores and pathogens cannot switch to phylogenetically distant taxa.
     - 1.3.10. The ability to use generalist mutualists (seed dispersers, pollinators, mycorrhizal fungi, nitrogen-fixing bacteria) greatly improves an alien taxon's chances of becoming invasive.
     - 1.3.11. Efficient competitors for limiting resources are likely to be the best invaders in natural and seminatural ecosystems.

1.3.12. Characters favoring passive dispersal by humans (e.g., small, soil-stored seeds) greatly improve an alien plant taxon's chance of becoming invasive.

1.4. Environmental compatibility

1.4.1. Climate matching is a useful first step in screening alien species for invasiveness.

1.4.2. Resource enrichment and release, often just intermittent (e.g., exceptionally wet years, canopy opening through logging, fire), initiate many invasions.

1.4.3. Propagule pressure (see 1.1.1) can override biotic or abiotic resistance of a community to invasion.

1.4.4. Determinants of invasibility (macro-scale climate factors, microclimatic factors, soils, and various community or ecosystem properties) interact in complicated ways; therefore, evaluation of invasibility must always be context-specific.

1.5. Relationship between species richness and invasibility

1.5.1. At the landscape scale, invasibility seems to be positively correlated with native plant species richness; at smaller (neighborhood) scales the correlation seems to be negative.

2. How fast?

2.1. Spread is determined primarily by reproduction and dispersal, but various extrinsic factors interact with these factors to mediate spread rates.

2.2. Spread rates based on local dispersal mechanisms (e.g., wind, birds, or mammals) greatly underestimate spread potential.

2.3. Rare, long-distance dispersal (often via mechanisms that cannot be predicted from an assessment of the ecology of a species) is hugely important for explaining population growth and spread over medium and long time scales.

3. Impact

3.1. Predicting the impact of invasive alien plants is much more difficult than predicting invasiveness.

3.2. Alien species that add a new function (e.g., nitrogen fixation) to an invaded ecosystem are much more likely to have big impacts than those that merely alter existing resource use levels.

4. Control, contain, or eradicate?

4.1. Early detection and initiation of management can make the difference between being able to use feasible offensive strategies (eradication) and the need to retreat to a more expensive defensive strategy (e.g., mitigation, containment).

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