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Review

Minimizing Risks of Invasive Alien Plant Species in Tropical Production Forest Management

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Abstract: Timber production is the most pervasive human impact on tropical forests, but studies of logging impacts have largely focused on timber species and vertebrates. This review focuses on the risk from invasive alien plant species, which has been frequently neglected in production forest management in the tropics. Our literature search resulted in 114 publications with relevant information, including books, book chapters, reports and papers. Examples of both invasions by aliens into tropical production forests and plantation forests as sources of invasions are presented. We discuss species traits and processes affecting spread and invasion, and silvicultural practices that favor invasions. We also highlight potential impacts of invasive plant species and discuss options for managing them in production forests. We suggest that future forestry practices need to reduce the risks of plant invasions by conducting surveillance for invasive species; minimizing canopy opening during harvesting; encouraging rapid canopy closure in plantations; minimizing the width of access roads; and ensuring that vehicles and other equipment are not transporting seeds of invasive species. Potential invasive species should not be planted within dispersal range of production forests. In invasive species management, forewarned is forearmed.

Keywords: alien species; invasions; risks; production forests; silviculture; management; tropics

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1. Introduction

Tropical forests, broadly defined, cover 1.66 billion hectares; 35% of the tropical land surface area [1]. Brazil (520 million ha), the Democratic Republic of the Congo (154 million ha), and Indonesia (94 million ha) have the most tropical forest. Most of this is natural forest, although the area of forest plantations is increasing rapidly. Approximately a quarter of the total tropical forest area is designated as production forest, but only a fraction of this area is formally managed and an unknown proportion of tropical timber comes from areas that are not designated for production. Tropical forests supply an estimated 9% of the global demand for timber and wood products [2,3], and the production and processing of these makes a significant contribution to incomes and employment in many tropical countries. However, current global concerns for tropical forests focus largely on carbon—they account for about half the total biomass carbon in the terrestrial biosphere and a third of global terrestrial carbon fluxes [4]—and biodiversity—they are believed to support more than half of global terrestrial biodiversity [5].

Timber production, both legal and illegal, is, with hunting, the most pervasive human impact on tropical forests, with perhaps 60% of the total forest area already impacted [6–8]. In comparison with conversion to agriculture, even high intensity logging has a much less severe impact on both biodiversity and carbon [9], although in some areas logging is often a precursor to clearance [10,11]. Post-harvest studies of logging impacts have largely focused on timber species and vertebrates, with fewer studies of non-timber plants and invertebrates. This paper focuses on a potential impact that has been largely ignored in the tropical forestry literature: the risk from invasive alien plant species.

Outside the tropics, the scale of invasion by alien species is currently unprecedented in terms of areas affected, and species involved [12]. In the last few decades, more alien species have been recorded, a greater total area has been invaded, and a greater variety of impacts has been documented [13], including economic, ecological, and health impacts in invaded regions [14,15]. In contrast, there has been little evidence, at least until recently, of invasive alien species as a major threat to native biodiversity in the continental tropics, although invasives are a major and widely recognized problem on tropical oceanic islands [16].

We consider both the risks associated with the management—or lack of management—of natural forests for timber production and those associated with plantations. The latter include both the risks to plantations from external invaders and the risks from plantations as a source of invasions. The focus is on invasive alien plants, with animal invasions mentioned only where they facilitate plant invasions. We identify potential problems from invasive species in tropical forestry and make suggestions for minimizing these risks in the future.

2. Methods

In addition to our own experiences in the Asian tropics, we used the Web of Science (WoS) as an initial guide to the international scientific literature. We searched using combinations of key words such as: "inva *", "alien species", "tropic *", "product *", "forest *", "silvicultur *", "plantation *" either as topic or title, and using timespan "all years". We also made use of Google Scholar, which includes a wider range of regional and local journals, as well as publisher-specific search engines, such as Springerlink. Finally, we searched widely on Google, which locates grey-literature publications that are not included in the scholarly databases. These searches were iterative and produced overlapping lists of publications. Moreover, there was considerable overlap between publications in their contents of relevant information. The final list of sources was pruned so as to include only those which added additional information on the topics of interest. In addition to the topic-specific searches, we used the recent literature on tropical silviculture as a guide to management practices that may influence biological invasions.

3. Results

In total, we found 114 publications (5 books, 13 book chapters, 11 reports and proceedings, 75 papers, 10 websites) with information relevant to our topic. Most report plant invasions into production forests—both natural and plantation—while the rest report plantation forests as sources of invasion.

3.1. Invasions into Production Forests in the Tropics

An understanding of the pathways by which alien invasive species enter production forests is essential for preventive management, but there is little information on this issue for the tropics. Some may enter from the surrounding non-forest—most often agricultural—matrix, but the resistance of continental forests to such invasions is well-documented (e.g., [17,18]) (Table 1). This resistance is usually attributed largely to dense shade [19], but may also reflect the preemption of other resources by a hyperdiverse native flora. Massive disturbance by logging operations (e.g., [11,20]), shifting cultivation (e.g., [21]), understory fires [22], or natural catastrophes [23], renders these forests susceptible to invasion from the matrix, but the invaders are usually eliminated as soon as a closed canopy is re-established. Roads also facilitate invasions into forested areas [24], as can logging vehicles [25], but few or no species spread beyond the roadside. Some exotic plantations in the continental tropics, however, seem to be highly invasible (RTC personal observations), most likely reflecting high light levels in the understory.

Forest invasions are probably more likely from botanical gardens, ornamental plantings, and plantation field trials, than from the non-forest invasive flora, since forest-adapted species make up a larger proportion of these plantings [24,26–28]. Moreover, although shade-tolerant species make up a small proportion of successful plant introductions, those that have established have the potential to invade even undisturbed continental forests [19]. A good example in tropical Asia is the subshrub *Clidemia hirta*, which is now found in a wide range of forest sites, from undisturbed rainforests in protected areas, where it is often the only alien plant species away from trails, through logged forests to exotic plantations ([29,30], personal observations).

In striking contrast to continental forests, tropical oceanic island forests have suffered massively from plant invasions [31,32] (Table 2). Although invasions are promoted by logging (e.g., [33]) and other disturbances, and are often facilitated by invasive alien animals [32,34], invasions of undisturbed sites have also been reported, with the invaders apparently using resources, such as light, that are not being fully utilized by the low-diversity native flora.

Table 1. Examples of invasions by aliens of tropical production forests (excluding oceanic islands).

References	Species	Native Range	Problem	Habitat Invaded
[20]	*Chromolaena odorata*	North America and Caribbean	alter the vegetation structure	humid lowland production forest in south western India
[35]	*Alstonia macrophylla*	Southeast Asia	no record	heavily logged and degraded forests in lowland southwestern Sri Lanka
[25,36]	*Urochloa maxima*	Tropical Africa	form monodominant stands	seasonally dry and selectively logged forest in eastern lowland Bolivia
	Urochloa brizantha	Tropical and south Africa	no record	
	Sorghum halapense	Mediterranean regions	no record	
	Cynodon nlemfuensis	Tropical Africa	no record	
	Rottboellia cochinchinensis	Africa, southern Asia,Australia	no record	
[24]	*Piper aduncum*	Southern America	no record	along logging roads in a lowland rain forest in East Kalimantan (Indonesian Borneo)
[37]	*Lantana camara*	Central and south America	reduce grazing land for wild herbivores	plantations and disturbed forests in Sri Lanka (and many other countries)
[38]	*Acacia mearnsii*	Southeastern Australia	displace native vegetation	plantations in southern India
[39]	*Eupatorium odoratum*	North and central America	affect plantation growth	Acacia, pine, eucalypt and other plantations in Vietnam
	Imperata cylindrica	Southeastern Asia	no record	

Table 2. Examples of invasions by aliens of production forests on tropical oceanic islands.

References	Species	Native Range	Problem	Habitat Invaded
[33]	*Passiflora tarminiana*	South America	form dense mats covering tree crown	disturbed environments in logged forest up to upper montane in Hawaii
	Ehrharta stipoides	Tropical Asia and Australia	inhibit regeneration of native species	
	Polygonum glabrum	Temperate and tropical Asia	no record	
	Rubus argutus	North America	no record	
[40]	*Rubus alceifolius*	Southeastern Asia	disturb regeneration of high-value native species	moist open gaps in lowland to upper montane production forest on Réunion island

3.2. Plantation Forests as Source of Invasion

Alien species are commonly—and preferentially—chosen for commercial plantations in the tropics [41,42]. Since the middle of twentieth century, more than 100 species have been deliberately introduced and planted for commercial forestry in the tropics [28], and additional alien tree species are currently being proposed for new uses, such as biofuel [43]. In commercial plantation forestry, tree seedlings are raised in nurseries, where they have the opportunity to acclimate to local conditions, before being planted over large areas at multiple sites [44,45]. A plantation of mature alien trees will then exert massive propagule pressure on the surrounding habitats, which will maximize the chance of establishment and spread. Moreover, plantations are served by road networks which can accelerate plant invasions [46]. This problem is acerbated by the tendency for tropical plantations to be adjacent to or interspersed with protected native forests. The result is the emerging issue of exotic plantations as a source of invasions of surrounding native vegetation, potentially threatening local biodiversity [47–49]. Plantation escapes are particularly serious as invaders because they are trees and thus both more likely to compete with timber trees and more expensive to remove than shrubs or herbs. When the aliens establish in a formerly treeless area, they may also have strong impacts on ecosystem processes and services [50].

There have been few detailed studies of invasions from tropical plantations, but many tropical species are listed in general reviews [43,51]. Species in the genera *Pinus* and *Acacia* (in the broad sense) account for many of these records, but many other species are also mentioned for one or more regions (Table 3). Other legumes are also prominent on tropical lists and nitrogen-fixing species, such as *Falcataria moluccana*, can modify the whole structure and function of a forest, particularly on oceanic islands [52]. Species grown for fuelwood, such as *Leucaena leucocephala* and *Acacia nilotica*, appear to be particularly invasive. Conversely, we could find no records of invasions from tropical plantations of *Eucalyptus* species or of the widely planted teak, *Tectona grandis*. It has been suggested that *Eucalyptus* species are non-invasive because the seeds are of low viability and poorly dispersed [53–55], but in such a large and diverse genus it seems unlikely that all species suffer from the same limitations. Given the recent massive expansion of pulpwood plantations in the tropics, and the planned expansion of biofuel crops, it is likely that there is a large "invasion debt" that will be realized over the next few decades [43].

Table 3. Examples of alien tree species that have escaped from tropical plantations and invaded surrounding native habitats.

References	Species	Native Range	Problem	Habitat Invaded
[56]	*Grevillea robusta*	Eastern Australia	suppressing the establishment of other species	native dry forests on Hawaii
[52]	*Falcataria moluccana*	Molucca, New Guinea, New Britain, Solomon Island	alter the functioning of native dominated forest	intact remnants of native wet lowland forest on lava
[33]	*Fraxinus uhdei*	Mexico, Costa Rica, Guatemala	suppress growth of native vegetation	natural logged forest; coast up to volcanic upper montane in Hawaii

Table 3. *Cont.*

References	Species	Native Range	Problem	Habitat Invaded
[57]	*Pinus caribaea*	South Mexico, central America, Caribbean	no record	ultramafic maquis on New Caledonia
[58,59]	*Pinus elliottii*	Southeastern USA	no record	Eucalyptus forest in Australia; cerrado and other ecosystems in southern Brazil
[60–62]	*Maesopsis eminii*	Tropical west and central Africa	form monospecific forest cover	selectively logged lowland to submontane rainforests in northeast Tanzania
[63]	*Alnus* spp.	Northwestern Africa	form pure stands	montane forest gaps in the Philippines
[37]	*Myroxylon balsamum*	Northern and south America	degrade the function of natural ecosystem	forest edges in the wet and intermediate zones of Sri Lanka
	Alstonia macrophylla	Southeast Asia	no record	secondary forests in the wet and intermediate zone of Sri Lanka
[37,38]	*Prosopis juliflora*	Central and south America	no record	thorn scrublands in Sri Lanka; abandoned agricultural land in India
[38]	*Acacia mearnsii*	Southern Australia	suppressing natural vegetation	montane "shola" forest in Kerala, South India
[64]	*Acacia mangium*	Northeastern Queensland	convert the habitat to monospecific stands	disturbed heath forest and native tree plantations in Brunei

4. Factors Affecting Spread and Invasion

Most alien species introduced outside their natural range are not invasive and very few that are invasive can invade forests. General traits that may favor invasiveness in alien species have been identified (Table 4), but their relevance to invasion of production forests has not been tested. General processes that favor invasion have also been suggested (Table 5) and all are supported by observations in the tropics. Forest invaders are facilitated by an existing tree canopy, as long as it is not too dense, while the impacts of propagule pressure, residence time, and seed dispersal ability are particularly clear in species that have spread from plantations. Enemy release has been shown to facilitate the invasion of Hawaiian forests by *Clidemia hirta* [65] and hybridization appears to have been involved in the origin of the highly invasive form of *Rubus alceifolius* on Réunion Island [66]. Among the invasive species listed in Tables 1 and 3, *Chromolaena odorata* has high specific leaf area, relative growth rate and relative investment in stems, and is a prolific source of wind-dispersed seeds [67–69], *Piper aduncum* is fast growing, freely flowering and fruiting, and well-dispersed by both birds and bats [21,70–72], invasive *Pinus* spp. produce frequent massive crops of well-dispersed seeds from a young age [42,73,74], and *Maesopsis eminii* is a fast growing, massively fruiting and well-dispersed [60,61,75,76].

Table 4. Traits associated with invasiveness in the literature.

Species Traits	Description	References
Physiology	aliens have higher photosynthetic capacity, more efficient nitrogen and water use, and longer flowering period	[77–79]
Specific leaf area (SLA)	aliens have higher SLA	[77–80]
Root-shoot ratio	aliens have lower root-shoot ratios, *i.e.*, they put more resources into above-ground biomass	[78,81]
Growth rate	aliens grow faster	[78–80]
Plant size	aliens are taller and have higher biomass	[44,78,79]
Fruit size and type	aliens have larger and/or fleshy fruits	[78,79,82]
Fitness	aliens have higher values for traits related to number of flowers or seeds, germination, survival, and/or mortality	[78]
Novel weapon	ability to release allelopathic compounds that are novel to native habitats	[80,83]
Biotic resistance	aliens are more resistant, e.g., to herbivory	[79,83]
Clonal spread	aliens can reproduce vegetatively	[44,77,79]
Phenotypic plasticity	aliens can acclimate to changing environments	[80]

Table 5. Processes favoring invasion success.

Processes	Description	References
Facilitation	existing trees and soil microbes may help the establishment of aliens; established aliens and the newly introduced species may facilitate each other	[80,84]
Propagule pressures	the total number of propagules arriving from the source populations is a key predictor of invasions, reflecting the number of source individuals, their fecundity, and their distance from the invasion site	[80,85,86]
Residence time	the time a species has been present is a major determinant of its cumulative propagule pressure	[82,87]
Enemy release	the absence of species-specific pests and pathogens may favor alien species over natives	[16,83]
Hybridization	hybridization may increase the genetic variation necessary to respond to changing environments and competitive regimes	[80,83]
Seed dispersal	fruits/seeds of aliens are more efficiently dispersed	[43,82,88]

5. Which Silvicultural Practices Favor Invasion?

As discussed above, intact continental tropical forests appear to be inherently resistant to plant invasions. This resistance is reduced, however, by any practice that opens up the canopy. In the silvicultural management of natural forests, these practices include tree felling, construction and use of roads and other infrastructure, cutting climbers and girdling competitors, and enrichment planting. The removal of canopy trees inevitably increases light availability in the understorey, thus facilitating invasion by light-demanding species. Construction of access roads, logging camps and other facilities opens large spaces in the forest for long-term use, not only facilitating the establishment of invaders but allowing them to build up their populations, thus increasing propagule pressure. Human activities in these areas, including the use of heavy machinery, such as skidders and tractors, can also directly disperse the seeds of potential invaders [89,90]. Enrichment planting in natural production forests may use native or alien species to increase the production of timber. The canopy opening treatments used to provide adequate light for rapid growth [91,92] can facilitate invasions, while planted aliens may themselves become invasive. In plantation forestry, land preparation, tree planting and maintenance activities in young plantations may all encourage invasive alien plant species. Land preparation requires careful control, due to the potential influence on seed germination [90]. Clear cutting of mature plantations creates large gaps that favour invasion [18,77]. Moreover, plantations trees may also become invasive (Table 3).

6. Potential Impacts of Invasive Plant Species

In production forestry, the invasive plant species of greatest concern are those with economic impacts. General reviews of the economic impacts of invasive plant species on forests tend to focus on insect pests and fungal pathogens (e.g., [93,94]). Plant invasions can sometimes be as costly e.g., kudzu in the southeastern USA [95], but there are few estimates of these costs for production forestry and none of these are from the tropics. Reported (or suspected) impacts of plant invasions in production forests include direct damage to timber trees from climbers, reduced recruitment of canopy trees, delayed filling of tree-fall gaps, inhibition of forest succession, and promotion of fires [93,96]. Young plantations are highly susceptible to overgrowth by climbers and fast-growing pioneers. The costs of invasions including reductions in timber yield as well as the costs of control efforts, which can be easier to estimate. Réunion Island spends two million Euros annually on controlling invasive plants [66], although this includes conservation forests and non-forest areas.

7. Management of Invasive Plant Species in Production Forests

The literature on invasive species management is too large to review here. In general, as the invasion moves from a potential threat, to the first few individuals, to patchy occurrences, towards an equilibrium with local environmental conditions, the management focus needs to shift from surveillance, to detection and eradication, to containment, and finally to adaptation to the new situation. Potential control measures for forest invaders have recently been reviewed by Miller *et al.* [97]. Biological control is probably underutilized in the tropics, but has started for the invasive *Rubus alceifolius* on Réunion Island [66].

Prevention is better than control, however. The package of practices known as Reduced Impact Logging (RIL) is designed to minimize disturbance through careful controls on tree felling, as well as log extraction and transportation [98,99], and is thus likely to reduce the risk of plant invasions, although it may also reduce the benefits of canopy opening for light-demanding timber species. The problems of invasions from plantations can be greatly reduced by the choice of alien species without a history of invasiveness, or by using species that are native to the area. Ecological theory suggests that mixed species plantations of natives will utilize resources, such as light, more completely than monocultures and thus resist invasions, although there is no data to back up this prediction.

At the landscape scale, minimizing the edge to area ratio may reduce invasions, as will combining higher intensity timber harvesting on part of a concession with protection of unlogged forest on the rest [100]. Adjacent lands uses—those within seed dispersal distance—are also crucial. Although foresters will rarely have authority over these areas, they need to be aware of potential sources of invaders, as well as natural habitats that may be vulnerable to threats from plantation species or invaders that become established in production forests. Negotiations with specific land-owners and educational campaigns aimed at general public awareness may both reduce invasion risk from the surrounding area. Foresters should also take an interest in regional and national policies that influence plant invasions, including quarantine regulations and reporting requirements.

8. Conclusions: Invasive Species and the Future of Silviculture in Tropical Forests

Invasive species problems are probably underreported in the tropics, but there is no evidence for a significant problem yet in tropical production forests, except in the inherently invasible forests on oceanic islands. However, the speed with which invasive plant problems have arisen in non-tropical forests (e.g., [97]) suggests that there is no excuse for complacency. Invasive species problems can only get worse, as new species invade and existing species build up their populations. The general issues are well understood: intact continental forests resist invasion by all but a tiny minority of alien plant species, none of which are currently causing significant problems, but any process, silvicultural or otherwise, that opens up the canopy increases the range of species that can invade, while access roads facilitate their spread. Climate change may create new problems. Although by no means all invasive species will benefit, there are good reasons to think that most invasive plant species will do better under climate change than many of the native species with which they compete [96].

Experience with forests outside the tropics suggests that, while early detection and eradication are the ideal answer to invasions, these have rarely been successful in practice. Similarly, quarantine measures that are practical in the advanced, but isolated, economies of Australia and New Zealand, will not be practical in developing tropical countries with long land borders (or hundreds of ports, like Indonesia). Currently the costs of forest invasions are born by governments and forestry companies, and there is no mechanism to transfer this burden to those responsible for introducing and spreading invasive species, such as the horticulture industry [93]. The practical difficulties of charging the costs of invasion to the economic sectors responsible are likely to prevent any change in this situation.

The forestry practices needed to reduce the risks of plant invasions are also well understood: continued surveillance for invasive species; minimizing canopy opening during harvesting and other silvicultural operations in natural forests; encouraging rapid canopy closure in plantations; minimizing the width of access roads and ensuring that vehicles and other equipment are not transporting seeds of invasive species. Conflicts between timber production and preventing invasions are most likely where forests are managed for relatively light-demanding timber species, such as mahogany (*Swietenia macrophylla*). Where possible, foresters should also try to ensure that potential invasive species are not planted in dispersal range of production forests. At the same time, plantation managers need to be certain that they are not themselves planting species with known invasive potential. Tropical foresters in general need better training in the detection and management of invasive species problems. The certification requirements of bodies such as the FSC (Forest Stewardship Council) can provide an incentive for better management of invasive species, since most of the above practices are included in the FSC's "Principles and Criteria" those managers must follow [101].

This paper was written to raise awareness of the risks from invasive alien plant species in tropical production forests. We would like, therefore, to conclude with a plea for information sharing. Many invasive species in the region we know well are not reported in the literature, so the information is not being shared above the country level and probably, in many cases, within the country. We also need to share information on successful—and unsuccessful—control measures, and on management practices that promote invasions. In invasive species management, forewarned is forearmed.

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Author Contributions

Both authors contributed to the literature search and the whole writing process.

Conflicts of Interest

The authors declare no conflict of interest.

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