CASE STUDY

Ecological Restoration of Lantana-Invaded Landscapes in Corbett Tiger Reserve, India

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ABSTRACT

Lantana (*Lantana camara*), one of the world's most troublesome invasive weeds, has become a menace in most of the protected areas located in tropical and subtropical belt of India. The lantana-infested landscapes not only are impoverished as habitats of wildlife but also contribute to human-wildlife conflicts owing to diminished ecosystem services. This paper is a case study of successful eradication and restoration of two lantana-invaded sites in Corbett Tiger Reserve, India. A method for eradicating lantana was developed using knowledge about its ecology, and, subsequently, weed-free landscapes were restored to productive grasslands and mixed woodlands using native species. The restoration of these areas to grassland communities has successfully prevented secondary invasions by lantana and other weeds and has enhanced the habitat quality for herbivores whose populations are vital for the survival of top carnivores such as tiger (*Panthera tigris corbetti*).

Keywords: Corbett Tiger Reserve, ecological restoration, grasslands, lantana (*Lantana camara*), protected areas

India's first national park, Corbett National Park, was declared in 1936. Ever since, there has been a steady rise in India's Protected Areas (PAs), which include National Parks, Wildlife Sanctuaries, and Tiger Reserves, especially after the enactment of the Wildlife Protection Act in 1972. In 1988, there were 54 national parks and 372 sanctuaries covering a total area of 109,652 km². There are currently about 597 national parks and sanctuaries in India, and these cover 154,572 km², or 4.74 percent of the country's geographical area. Launched in 1973 with nine reserves covering an area of 16,339 km², the Project Tiger program has been extended to 28 reserves in 18 states, encompassing 37,761 km² of tiger habitat. However, the management of these protected areas is a major challenge with problems of habitat fragmentation, man–wildlife conflicts, poaching, forest fires, and invasive species. In most of these PAs, the peripheral buffer zones (which act as buffers from developmental and other human activity) and forest gaps (firelines, forest guard quarters, etc.) in the core areas are invaded by non-native invasive species. The worst invasive weeds of PAs include lantana (*Lantana camara*), bittervine (*Mikania micrantha*), thoroughwort (*Chromolaena* sp.), tropical whiteweed (*Ageratum conyzoides*), Santa Maria feverfew (*Parthenium hysterophorus*), and pignut (*Hyptis suaveolens*).

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Lantana is one of the world's 100 worst weeds and is invasive in over 60 countries, particularly in tropical and subtropical regions outside its native range in the neotropics (Walton 2006). It is a low, erect or subscandent perennial shrub growing to a height of 2.5 m or more and forming dense monocultures. It reproduces primarily by means of copious seed production and also by vegetative propagation from cut stems. The juicy pericarp attracts a large number of dispersal agents, among which birds play a major role. The plants can grow individually as clumps or form dense thickets crowding out the native species. It has demonstrated allelopathic potential and can considerably reduce the seedling vigor of native species (Gentle and Duggin 1997, Day et al. 2003). It infests disturbed forest ecosystems, where it dominates understory species, blocks natural succession, reduces biodiversity, outcompetes native pasture species, reduces productivity, increases soil erosion, and causes illness and death of livestock (Sankaran 2007, Walton 2006). The dense understory of lantana inhibits the seedling recruitment of native tree species in the forest, leading to the depletion of native trees (Singh et al. 1995, Sharma et al. 2005, Bhatt et al. 1994, Kohli et al. 2004). It has invaded the majority of Indian pasturelands (13.2 million ha) beside other areas, and the cost of its control is estimated to be US$70 per hectare (Singh 1996). Therefore the damage from lantana to pastures alone is estimated to be US$924 million per year (Pimentel et al. 2001), and this does not include vast tracts of disturbed forest colonized by lantana.

It is not clear how it arrived in India; neither is it known when it reached Corbett National Park, although there are anecdotal references to introduction of lantana as an ornamental in the early 20th century near Nainital. Lantana might have been introduced in India on multiple occasions in late 1800s—as an ornamental in Coorg (Hiremath and Sundaram 2005) and as biohedge in Calcutta in the early 19th century (Hakimuddin 1929, Pereira 1919). Hakimuddin (1929) also gives an account of its introduction and spread in Nainital District around 1905. Per this account, it was confined to hedges and had sparse distribution until 1911, but by 1929, lantana had spread from its point of introduction to about 40 km in all directions, forming dense thickets covering farms, pastures, fallows, and forest areas.

Frugivorous birds are known to play a major role in the dispersal of fleshy-fruited invasives (Gosper et al. 2005, Buckley et al. 2006), and they may have dispersed lantana from villages and townships, where it was grown as a hedge plant, to the disturbed forest tracts in the periphery of Corbett Tiger Reserve (CTR), particularly intensely grazed habitats. Today, it has invaded all the plant communities, ranging from grasslands to moist deciduous forests, of CTR—in both the buffer areas and several patches in the core area.

Despite a fairly large amount of published literature on the taxonomy, biology, ecology, and control and management of lantana, no successful strategy for control and management is available. The landscapes colonized by lantana are degraded ecosystems and pose several challenges for restoration, including means of removing invasives and augmenting ecosystem redevelopment. We have attempted to tackle the problem of lantana in CTR with a three-step approach: 1) understanding the biology of lantana with the objective to develop control measures; 2) developing simple and effective control measures; and 3) evolving a suitable restoration program, keeping in view the requirements of the stakeholders and the reference ecosystems. In this paper, we present our observations and experiences on the eradication of lantana, its control, and ecological restoration of lantana-eradicated areas in CTR.

Study Area

Corbett National Park is the oldest National Park in India, located between 78°5' E and 79°5' E longitude and 29°25' N and 29°40' N latitude (Figure 1) in the state of Uttarakhand. Corbett Tiger Reserve was created with the National Park and additional Reserve Forest area as part of the nine Tiger Reserves created at the launch of Project Tiger in 1973, with the specific aim of saving the dwindling tiger population. The CTR spreads over an area of 1318.5 km^2 in the foothills (Shivaliks) of northwestern Himalaya in the Siwalik-Terai biotic zone of the Indian Himalayan ranges. The reserve is adorned with a unique assemblage of Himalayan flora and fauna and well known for a healthy population of tigers. In 1991, an area of 797.72 km^2 was added as buffer for the Corbett Tiger Reserve and includes the whole of Kalagarh Forest Division and 96.70 km^2 of Ramnagar Forest Division. The CTR management is headed by the Field Director with headquarters at Ramnagar.

The area was declared as a National Park not only because of its biological richness and as prime tiger habitat but also because of its hydrological function as a principal catchment area of the Ramganga River, a tributary of the Ganges. The landscape of Corbett encompasses a network of monsoonal and perennial first-, second-, and third-order streams having wide riverbeds and riverine stabilized islands, floodplains, valleys, gentle hillslopes, hilltops, and marshlands. These different habitats support a wide range of communities, ranging from seral grassland communities, shrublands, and moist and dry deciduous forests with sal (*Shorea robusta*) as the dominant tree to patches of mixed deciduous forests, bamboo thickets, and grasslands. The diversified vegetation types support a healthy population of herbivores and carnivores including the tiger.

The buffer area of the park includes several villages where lantana was introduced as a hedge plant to protect the crop fields from herbivores. Over time since its establishment, there has been an increase in human–wildlife conflicts, due mainly to large livestock maintained by the few villages located in the buffer area. There were frequent instances of cattle grazing within the park areas and thus competing with other herbivore populations. There were also several instances of wildlife raiding the agricultural fields and cattle takings by tigers and leopards. As per government policy at the time, there was pressure to expand the PA and to relocate the villages with their growing livestock herds. As villages were relocated from within the PA to elsewhere, large tracts of lands once cultivated or settled were rapidly invaded by lantana (Sahu and Singh 2008) and other weeds. In 1990–93, Dhara and Jhirna, two villages situated on the southern boundary of the reserve, were relocated to the Firozpur–Manpur area and Ampokhra, situated on the Ramnagar–Kashipur highway. Another village, Laldhang, located along the southern boundary of the park is presently being relocated. These villages have been relocated outside the park to aid conservation programs, and the areas thus vacated have been included in CTR as buffer zones. It was expected that the forest would regenerate; but as years passed, no significant forest regeneration occurred, as the native species were outcompeted by weeds. At present no villages remain inside the Tiger Reserve, but there are 92 villages within 2 to 3 km of its boundary. The human population of these villages is around 65,982, and the livestock population around the reserve is 44,416 (Ministry of Environment and Forests 2001). Therefore there is persistent pressure on the Park's boundary from these villages. The need is strong to

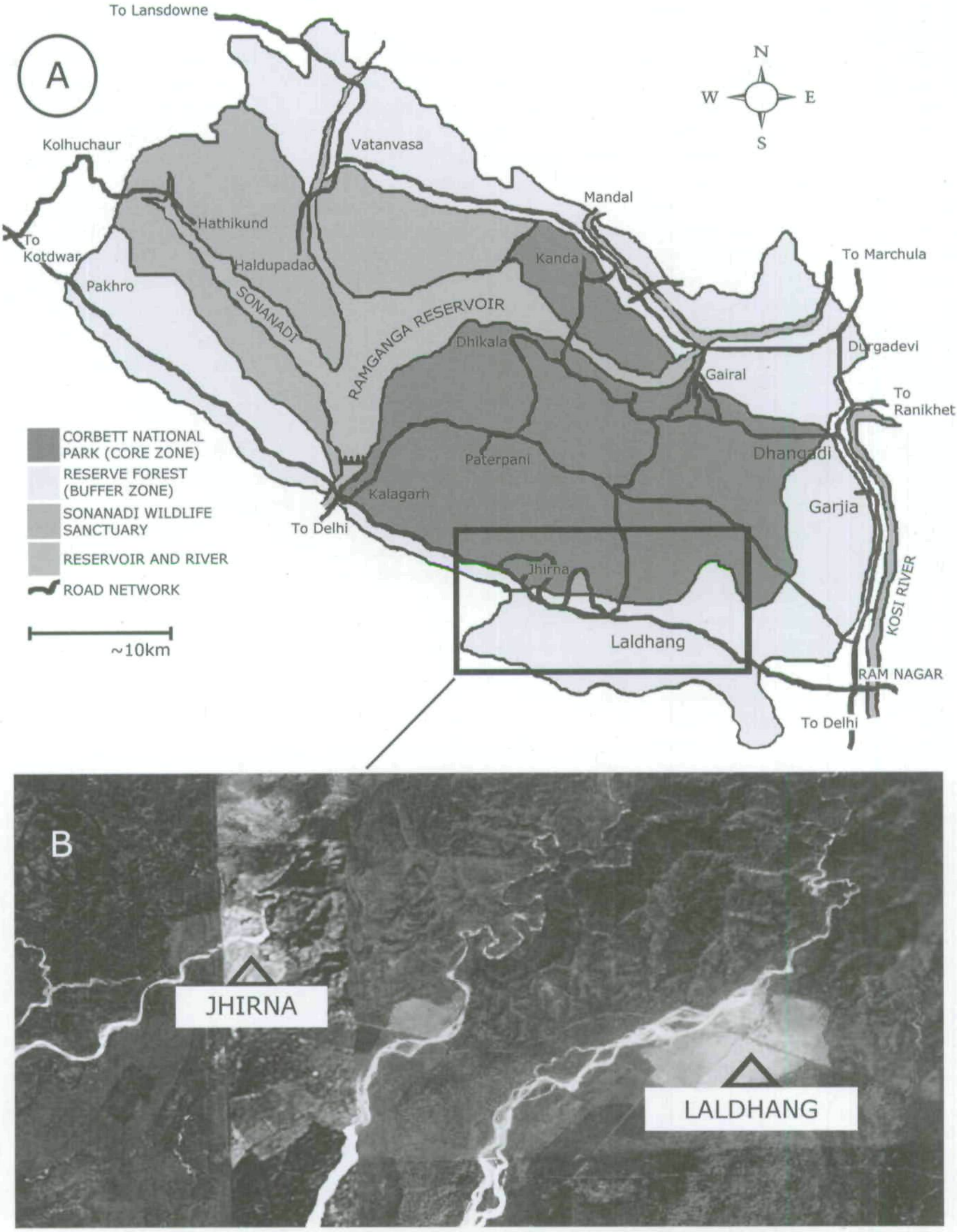

Figure 1. Schematic map of Corbett Tiger Reserve (A) and satellite image of the inset from Google Earth (B) showing the experimental plots at Jhirna and Laldhang.

restore even the buffer zones that are impoverished by lantana, to meet the purpose for which they were created.

Dwindling prey base and human–wildlife conflicts are considered the prime causal factors for the dwindling population of tigers in the wild across the country (Seidensticker et al. 1999, Johnsingh and Negi 2003, Johnsingh et al. 2004). For a long time the management was not serious about the infestation of the park with lantana on the grounds that it serves as a food base for some species of birds. However, the park managers have now realized that the spread of lantana in the entire park is changing the landscape, threatening its biodiversity, preventing natural succession, and enhancing the frequency of human-wildlife conflicts owing to increased crop raiding by herbivores in nearby villages.

Traditional Control Methods

A number of methods, including physical, chemical, and biological methods, have been used to control and manage lantana invasions in different countries. Day and colleagues (2003) summarized the status of current control methods as inadequate and infeasible owing to the sheer size of the infestations, low land values, and lack of incentives for control. The biology of lantana and lack of site-specific information on its ecology are major bottlenecks in developing effective tools for its management. It has yet to be recognized, for instance, that habitat degradation has triggered the invasion of lantana and that a final solution has to come in the form of habitat restoration. In India, forest managers recognize lantana infestation in PAs as a major problem, and they are currently using a variety of control methods. The physical methods that have been in practice for controlling lantana include 1) chopping the main stem at the base; 2) clipping aerial shoots 10 to 30 cm above the base; 3) burning the clumps; and 4) grubbing (total uprooting).

Some of these methods do bring about a short-term reduction in lantana cover. But with the onset of monsoons, profuse coppicing from multiple growing points triggered by the suppression of the apical meristems takes place, and soon lantana overshadows the ground, preventing the germination and establishment of other species, particularly natives. Clipping is totally ineffective and only causes the clumps to spread and become hardier. Burning results in coppicing from the buried meristematic zone and also increases soil erosion. Burning on a large scale is normally not resorted to in PAs, as the fire may spread to adjoining areas and because some varieties have a climbing habit and can cause crown fires. Grubbing, besides being labor intensive, disturbs the soil, which exposes the buried seeds of lantana and leads to their rapid germination. The consequence of most of these methods has generally been vigorous regeneration of lantana.

In another attempt to control lantana in CTR, giant reed (*Arundo donax*), a perennial grass, was planted in one of the lantana-infested areas in the core area of the park after burning. Within five years, the giant reed–lantana community became dominant in the area, with both species spreading to new areas. It was realized subsequently that giant reed itself is an invasive species and is not preferred by herbivores. The current spread of lantana all over the CTR demonstrates the ineffectiveness of the traditional control methods in use for over two decades. Our field observations of traditional control measures raised the following two questions: Where and how does proliferation occur after clipping, chopping, or burning? What are the modes of seed dispersal in lantana and how does it colonize new areas?

To address the twin challenges posed by lantana invasion—those of its control and habitat degradation, we selected two relocated village areas, Jhirna and Laldhang, in the buffer zone of CTR as our study sites. At both sites, 2 ha rectangular plots were demarcated and initial conditions were recorded (Figure 2A) and subsequently used to develop a control and management strategy. We studied the field biology and ecology of lantana with a view to developing an effective control and management strategy. The aspects investigated include 1) magnitude of the invasion; 2) distribution of growth points (vegetative reproduction); 3) characteristics of the root system; and 4) seed production, modes of seed dispersal, and seed germination.

Field Biology and Ecology of Lantana

Magnitude of Invasion of Lantana in CTR

A survey of core and buffer zones of the park was carried out using stratified random sampling to assess the magnitude of invasion and to understand the vulnerability of different habitat types to lantana. In each habitat type studied, a total area of 0.5 ha was sampled using 10 m × 10 m quadrats (n = 50) spread randomly across the habitat.

We observed that lantana was found everywhere except in dense, closed forests and the percent relative density (the ratio of density of lantana to the density of all plants in the 0.5 ha sampled) varied from 0.1% to 82.3% (Table 1). The stands along forest roadsides comprised only old clumps, and no new saplings or young plants were observed. Abandoned arable village land fields also had a high relative density (22.9%) of lantana. Except for a few perching trees, no other native species were found in densely infested areas.

Distribution of Growing Points

We examined the growth pattern of 25 individual lantana three months after each of the following treatments: 1) chopping at about three-fourths of the height of the plant (leading to about 25% removal at about 1.5 m from the ground); 2) chopping down

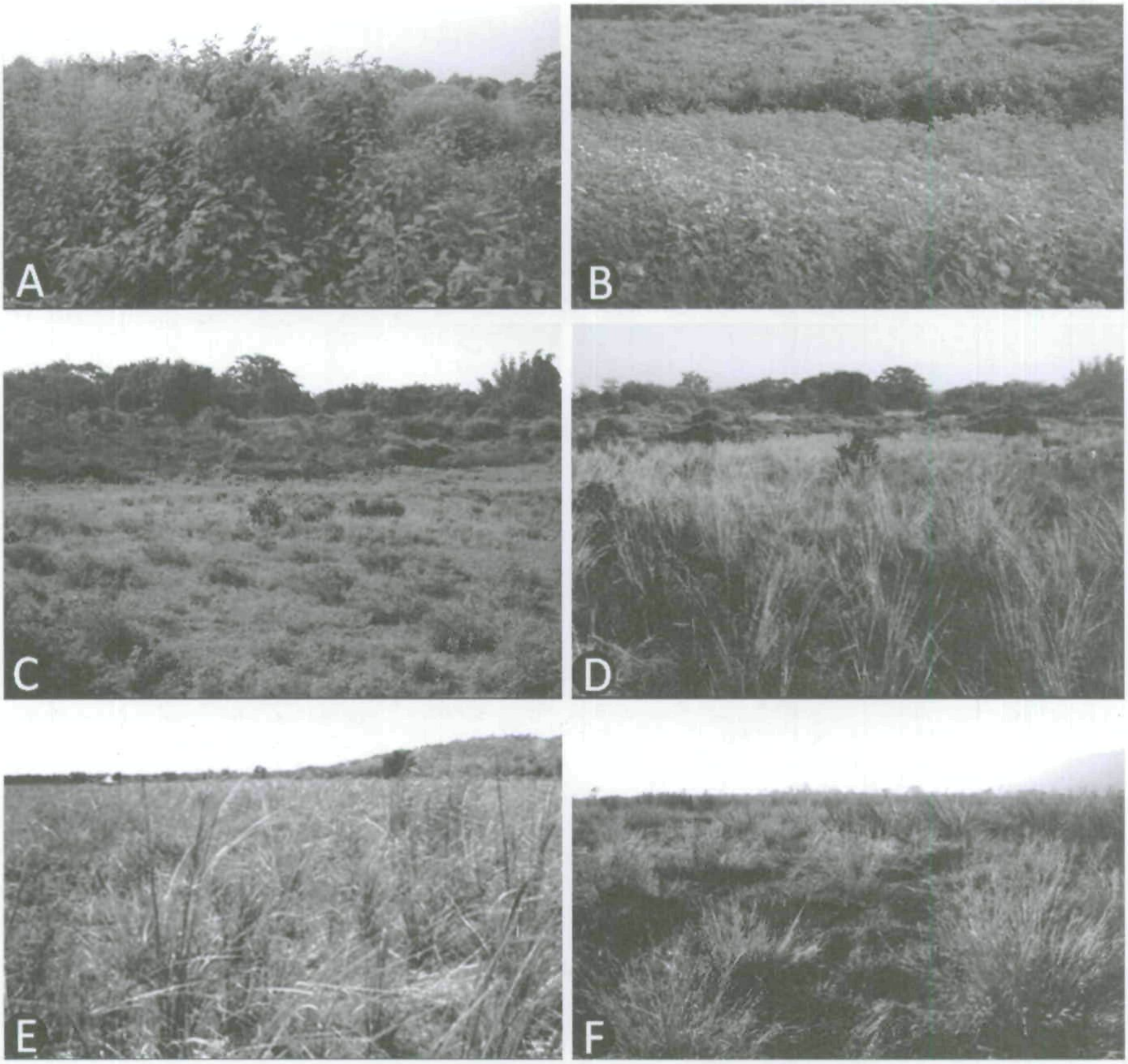

Figure 2. Photo series of treatment plots: A) massive original colonization by lantana in Jhirna; B) secondary invasion of the same plot after removal of lantana; C) the same plot of Jhirna, two years after restoration with selected legumes and grasses; and D) and after three years of restoration; E) restoration plot at Laldhang showing development of grasslands two years after lantana removal; and F) same plot with grasslands and scattered shrubby legumes after three years. Photos by Suresh Babu

to the base; 3) burning; and 4) control. Growing points are located from the lowest node to the uppermost node of the main stem and lateral branches. The meristematic zone, located at the transition between stem and root, was identified as the active coppicing zone in lantana based on observations summarized in Table 2. This zone is usually buried in the soil (up to 10 cm depth). Coppicing was profuse from this zone after burning and chopping at the base, both of which remove all the aerial growing points. It is interesting to note that the subterranean coppicing zone was most active when the aerial growing points were removed by complete chopping or burning of the aerial biomass and least active in naturally grown plants (Table 2).

The auxiliary shoots arising from the lowest nodes of the main stem are usually prostrate in their lower halves, and rooting occurs at the nodes on the prostrate portion of the stem. These shoots sometimes become independent plants when connection with the main plant is severed. This is the only method of vegetative reproduction we observed. No root suckers were observed, and no fragments of aerial branches were found to be capable of rooting and developing into plants.

Root System

Lantana has a shallow root system. The first-formed taproot is stout, tapers gradually, and penetrates up to a depth

Table 1. Density and percent cover of lantana (*Lantana camara*) across different habitat types. Seedlings were not included in the survey.

Landscape	Density (plants/m²)	% Cover
Riverbeds	0.0077	6.1
Stabilized riverine islands	0.0021	2.2
Floodplain without grasslands	0.0144	16.84
Floodplain grasslands	0.0027	2.26
Forest roadsides	0.0909	82.23
Grasslands with perching trees	0.0072	7.18
Arable land abandoned by villagers	0.0126	22.05
Open forests with patches of grasses	0.0026	2.8
Natural Gaps	0.0021	2.17
Dense closed forests with understory	0.0012	1.2
Marshy flatlands	0.0003	0.118
Surface drainage channels	0.0048	1.12

Table 2. Growth pattern in lantana (expressed as mean number (± SD) of shoots per coppicing region of the plant (n = 25) under different traditional control methods applied in mid-June 2005; observations recorded in mid-September 2005 after three months of monsoon.

Coppicing Region	Chopped	Chopped from base	Burned	Control
Nodes in top one-third	—	—	—	38.1 ± 16.7
Nodes in middle one-third	18.4 ± 8.2	—	—	12.4 ± 7.2
Nodes in lower one-third	28.5 ± 7.1	—	18.3 ± 5.1	4.3 ± 2.2
Root–shoot transition	12.5 ± 3.8	61.8 ± 10.2	42.7 ± 15.4	1.8 ± 0.6

of 0.2 m. From the upper portion of the main taproot, stout lateral roots arise and some of these spread horizontally in the topsoil. All along these laterals, fine rootlets with copious root hairs are produced. The high investment in shoots rather than the root system suggests that the species utilizes its energy more for vegetative growth and reproduction.

Seed Biology

Lantana reproduces primarily by seed and is a copious seed producer. The seed is a pyrene (seed with stony endocarp) enclosed within the sugary, juicy pericarp of the fruit, which is usually black in color and eaten by birds. The fruit, which ranges from 4 to 6 mm, is available nearly throughout the year.

The percent fruit set of plants, estimated from the average number of fruits produced out of the average number of flowers, was 68.95% in the Jhirna area. On average, about 1,660 individuals per hectare were present in a pure stand of lantana. From these empirical observations, we estimated that over 1.2 million fruits are produced per hectare by pure stands of lantana in Corbett. This reproductive output highlights the tremendous potential that this species has for spreading into newer areas of the Park and the propagule pressure it exerts on nearby habitats.

We collected baseline data on dispersal vectors of lantana because it was crucial to understand the complex patterns that may result from the interaction between lantana and its dispersal agents, as shown by earlier studies on fleshy-fruited invasive plant species (Glyphis et al. 1981, Stansbury 2001, Renne et al. 2002, Buckley et al. 2006).

So far, we have identified 18 species of birds foraging on the fruits of lantana. These include common birds, such as the red-vented bulbul (*Pycnonotus cafer*), magpie robin (*Copsychus saularis*), common myna (*Acridotheres tristis*), and Indian cuckoo (*Cuculus micropterus*). All these are generalist frugivores, and their role in dispersal of lantana seeds is implicated in some other studies also (Bhatt and Kumar 2001). Therefore lantana has been able to utilize the generalized mutualistic interactions in the invaded habitat for its spread and colonization.

These birds disperse the seeds beneath perching trees, which are mostly trees that provide shelter and have fruits of dimensions similar to lantana. We prepared a tentative list of perching trees for the study area and found large concentrations of lantana seedlings underneath these trees. The most common perching tree was ber (*Zizyphus nummularia*), a common fruit-bearing tree native to this region. The dispersed lantana seeds are also carried by water along surface drainage channels in the rainy season. Seeds deposited under perching trees and those carried by water currents usually germinate and establish seedlings. In other words, the initial sites of lantana colonization are around perching trees, surface drainage channels, and riverbeds, all of which are usually open habitats. It has been shown that passage of lantana seeds through the gut of dispersers increases germination rates (Mandon-Dalger et al. 2004), as is also the case with several other invasive species employing mutualists for their spread (Panetta and McKee 1997).

Several attributes of the species that enable it to colonize disturbed habitats have come to light. Of particular importance are the ability for vegetative propagation and employment of generalist frugivores that use the perching trees in the *chaurs* (grasslands along floodplains) for dispersal. We also observed that seeds of lantana failed to germinate in the absence of adequate sunlight and moisture. Any attempt to restore these invaded landscapes necessitates effective control measures that address the regeneration ability of the species. The lantana density in different landscapes is such that any intervention limited to a small area of the park is likely to be ineffective, as propagules would soon arrive from nearby areas. It must also be followed up with restoration using

Figure 3. Stump of lantana removed by cut-root-stock method: A) root-shoot transition and emerging young shoots; and B) inverted clumps of lantana removed by this method, kept for drying. Photos by Suresh Babu

competitive native species that can resist reinvasion by lantana and other weeds. Following these insights from field biology and from other experiences in controlling lantana (Day et al. 2003), we developed a two-pronged strategy—eradication and restoration—for the problem of lantana in CTR and put this strategy to test at the 2 ha plots at Laldhang and Jhirna.

Development of a Control Strategy and the Cut-Root-Stock Method

Based on our studies of lantana in CTR, a simple, cost-effective physical method has been developed for the removal and for long-term management of lantana infestation. The method was designated as Cut Root-Stock (CRS) method, as it involved a cut below the root–stem transition zone (Figure 3A) identified as the active zone of proliferation for lantana (CEMDE 2007, Pathak et al. 2006). This method involved chopping the main taproot 3–5 cm below the ground surface with a few hits, using a *kudaal* (a locally available heavy digger) with a long handle. Then the clumps were lifted and placed upside down to ensure that all the vegetative parts dry up (a minimum of 2–3 months). These dried clumps were collected in a small area for burning (Figure 3B). Subsequently, perching trees were located and the saplings were removed from under their canopies and along the nearby surface runoff zone. Continuous monitoring was required in the area where lantana was eradicated, including manually uprooting seedlings of lantana, if any, for a year. The best time to eradicate lantana was in peak summer season when lantana clumps bear few or no mature fruits. We realized that until lantana is removed from all areas contiguous with the experimental plots, the chances that the propagules would soon arrive was very high. Encouraged by the initial results of the CRS method, and with the objective to completely remove lantana from all areas of CTR, the management undertook massive scaling up, during which lantana was removed in different parts of CTR including Dhikala, Gairal, Sarpadhuli, and Bijrani Ranges.

The main advantage of the CRS method is that it does not involve pruning of aerial branches or digging and thus is less labor intensive. This method also results in very little regeneration of lantana by vegetative propagation and from seed banks. A single laborer can remove, on average, about 20–50 clumps per day and the expenditure per hectare is about INR 2,000–4,000 (US$40–$80)—in contrast to grubbing, where a single laborer removes only 8–10 clumps per day and the expenditure range is INR 8,000–10,000 (US$170–$200) per hectare. However, the cost of removal per hectare varies according to the age of the clumps, the terrain, and the density of lantana.

As we observed in Corbett, simple removal of lantana by CRS method was not enough. If the land was left vacant after eradication, it was soon subjected to secondary invasion by invasive weeds like Santa Maria feverfew (*Parthenium hysterophorus*), *Senna tora*, *S. occidentalis*, llima (*Sida cordifolia*), wireweed (*S. acuta*), and also lantana (Figure 2B). Therefore we concluded that merely removing lantana will not solve the problem of ecological degradation of these areas and it is necessary to develop a suitable restoration program for these weed-free areas.

Restoration of Weed-Free Landscapes

Our restoration technique consisted of four essential steps. The first involved the identification of reference ecosystems by field ecological surveys in relatively undisturbed areas of the Park with similar ecological settings. After transect surveys (Krebs 1989) of the areas around Jhirna and Laldhang, we concluded that both areas are similar to existing *chaurs* nearby and that it is most appropriate to develop these "lantana eradicated landscapes" into grasslands and mixed woodlands. After referring to literature on the flora of the foothills (Babu 1977, Pant 1976), we identified 28 grass species and 15 legume species that have high forage value to herbivores, like chital (*Axis axis*) and sambar (*Cervus unicolor*), that form the prey base for carnivores and also play a role in the early succession in chaurs.

The second step was to define target conditions, and for this, the identification of the requirements of the stakeholders (in this case the park management) was a prerequisite. The prime concern of the park management was to augment the dwindling prey base for top carnivores like tigers. This could be achieved through the development of grasslands and mixed woodlands that would supplement the foraging requirements of herbivores. Since both Jhirna and Laldhang are in the tourist zone of the Park, an indirect benefit was the ecotourism potential of these areas.

The third step was the development of field nurseries and a sequential introduction of selected species into the lantana-free landscapes. A field nursery was established 3 km away at Dhela, which had perennial water supply from a stream. Selected grass species and their seeds were collected from the buffer areas within 5 km of the plots, along with several leguminous species that are found locally. Propagules were transferred from this nursery to both the sites. Transplants of grasses, consisting of a portion of the rhizome having one to three culms, were planted at random with a spacing of 8 to 10 cm. Saplings of legumes were raised in poly-bags and were planted on the plots. In the subsequent year, the seeds of grasses and legumes were mixed with farmyard manure and soil, made into pellets, and broadcast directly on the plots. A mix of annual and perennial grasses was used, avoiding several species of grasses with invasive tendencies like cogongrass (*Imperata cylindrica*) and giant reed (*Arundo donax*). The density of tall grasses was kept low and high densities of nutritious legumes, like several species of indigo (*Indigofera* spp.), flemingia (*Flemingia* spp.), *Atylosia*, and ticktrefoil (*Desmodium* spp.), were maintained in the initial stages. Subsequently, saplings of several native trees, particularly leguminous trees like albizias (*Albizia* spp.), acacias (*Acacia* spp.), Indian rosewood (*Dalbergia* spp.), fruit-bearing shrubs such as *Zizyphus*, and trees such as alangium (*Alangium javanicum*), Assyrian plum (*Cordia myxa*), chamror (*Ehretia laevis*), and *Syzygium* were introduced in scattered patches. Plantings were carried out between July and October (during the monsoon) every year. Legumes were introduced at six-month intervals, as initial mortalities were high.

The fourth and the most important step involved monitoring and follow-up activities such as manual weeding under perching trees and along drainage channels. A list of the perching trees (candidate lantana dispersers) based on field surveys was provided to the field staff of the forest department. The most common perching trees in the area are alangium, Assyrian plum, sacred garlic pear (*Crateva religiosa*), chamror, emblic (*Phyllanthus emblica*), figs (*Ficus* spp.), gardenia (*Gardenia turgida*), glycosmis (*Glycosmis pentaphylla*), *Miliusa velutina*, Java plum (*Syzygium cumini*), common jujube (*Zizyphus jujuba* [= *Z. zizyphus*]), and jhar beri (*Zizyphus nummularia*). This greatly facilitated monitoring and follow-up activities, even without the presence of experts on-site to identify the species. The park management circulated this list to all the forest ranges where the scaling up of lantana control and management was undertaken. Lantana seeds buried under clumps removed by the CRS method failed to germinate because the restored community strongly competed for light, and also owing to the crowding effect. Continuous monitoring of the natural and manmade forest gaps and landscapes that harbor perching trees, riverbeds, and surface drainage channels for seedlings of lantana and their uprooting are essential for the successful eradication of lantana.

Results and Outreach

The two plots established at Jhirna and Laldhang, using the integrated control and restoration strategy outlined above, are now used for demonstration of the technique. At both sites, the original relative density of lantana clumps varied from 80% to 100% and were devoid of native species except for a few scattered perching trees. Within two years of the restoration program at CTR (June 2005 to June 2007), both demonstration plots harbored grassland communities with annual and perennial native grasses and legumes. As of August 2008, seedlings of several other native species are also found as a part of the developing community, suggesting that the habitat is improving (Figure 2C–F). The recorded increase in the number of species and the greater proportion of grasses and legumes in both plots compared to the initial conditions are of particular importance (Figure 4). The control areas had fewer species, having experienced some harvesting as they are near the relocated villages. It seems plausible that some of the grass species may not persist over the long term on account of competitive exclusion.

As of August 2008, more than 150,000 grass clumps and more than 5,000 saplings and seedlings of legumes were planted in CTR in areas where lantana had been removed, covering an area of more than 1,600 hectares. Much of this effort was made possible only by active involvement of Corbett management. At present the follow-up activities involve monthly removal of seedlings, if any. Already there are very few seedlings arriving on these plots, and we believe that as nearby sources of seeds are removed and effective competitors like grasses and legumes are present in adequate quantities; a reinvasion by lantana is unlikely.

The tree saplings have high survival rates (measured annually) because of modification of soil conditions and the habitat by short grasses such as buffelgrass (*Pennisetum ciliaris*), sabaigrass (*Eulaliopsis binata*), tanglehead (*Heteropogon contortus*), watercrown grass (*Paspalidium scrobicularis*), Bermudagrass (*Cynodon dactylon*), and smutgrass (*Sporobolus indicus*), as well as leguminous species like salpani (*Desmodium gangeticum*), threeflower ticktrefoil (*D. triflorum*), *Flemingia bracteata*, *F. fruticosa*, *F. macrophylla*, *Indigofera astragalina*, and rough-hairy indigo (*I. hirsuta*). The plots were browsed by chital and there was some mortality, but it was not a serious impediment because herbivore numbers were small, as most of the wildlife had moved away from this area since it had recently been a settlement.

Both experimental plots are now fully covered with a carpet of several grass species and legumes, with scattered trees (Figure 2C–F). At Laldhang, the CTR management has scaled up the restoration plot to 64 ha. In order to prevent repeated encroachment and cattle grazing from nearby villages, the management has erected an electric fence around the entire plot until the grassland–mixed woodland community is established (at least another two years). Despite this, droppings of chital and wild boar (*Sus scrofa*) have been observed in the fenced plot. The Jhirna plot was left unfenced because there was no threat of cattle grazing. This plot is now frequented by large herds of browsers like chital and sambar, which form the major prey base for carnivores. So far there have been three recorded tiger sightings at Jhirna in the vicinity of the restoration plot.

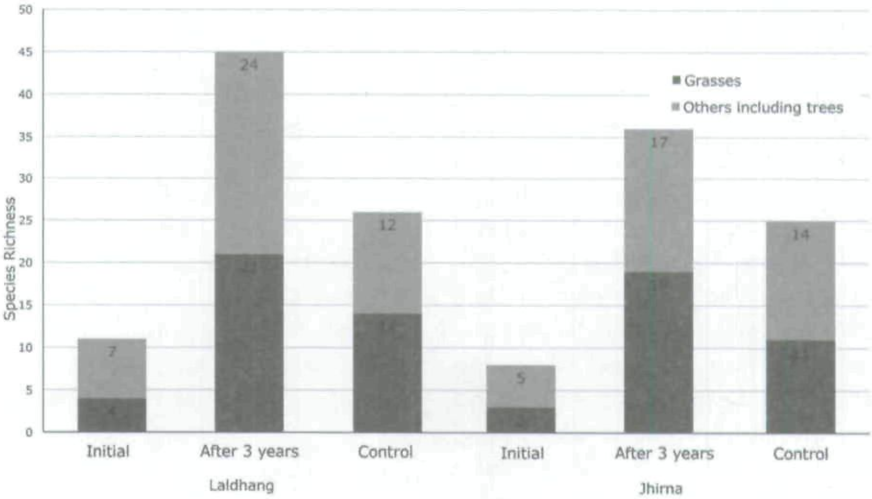

Figure 4. Comparison of species richness at the the two study sites following restoration. Control sites were forested areas in the proximity of the experimental plots. Data on species occurence was collected using ten 100 m² quadrats at each of the sites.

Several workshops and hands-on training programs were also held to enable the foresters and park managers to scale up the lantana control and restoration measures, with field visits to the plots and demonstration of the technique employed. Various aspects of this model, including the costs and benefits of clearing lantana and then converting the landscape into productive grasslands and woodlands, were highlighted to gain wider acceptance for the model. A simple manual was developed and widely circulated to aid the foresters in removing lantana by the CRS method and to identify the grasses and legumes used in the Corbett model.

Subsequently, not only the CTR management but also other PA managers of Uttarakhand State have adopted this model and are actively engaged in this program at Rajaji National Park, Landsdowne Forest Division, and Nainital Forest Division. Forest departments of other states of India have also been convinced by the effectiveness of the approach and have already removed lantana from several hundred hectares of forest land, particularly around Panchmarhi Biosphere Reserve in Madhya Pradesh and Kalesar National Park in Haryana.

One of the major reasons for the popularity of the CRS method has been economics and the fact that the restored patches do not require aftercare like watering, since all the species used are local. In CTR, the approximate cost of removal of lantana followed by restoration as described ranged from INR 6,000–9,000 (US$125–$187) per hectare. However, across different PAs of Uttaranchal where this strategy was subsequently followed, this method of restoration cost between INR 4,000–10,000 (US$83–$208) per hectare. The range in cost is explained by the kind of terrain (rocky, slopes, alluvial soils, etc.) and the age of the clumps.

Implications for Management and Lessons Learned

The PA network in India is the last refuge for a large number of threatened and endangered flora and fauna. It provides a variety of ecosystem services that support the enormous livelihood requirements of the country. One of the major problems faced by many PAs in India today is habitat degradation and fragmentation and subsequent colonization of these disturbed habitats by invasive species. The vast tracts of forest and community lands covered by invasive weeds pose twin challenges: control and eradication of weeds and restoration of the weed-free landscapes to prevent further invasions and improve habitat conditions. In this study, we examined the biology and ecology of lantana in order to understand its invasive nature, and based on that understanding, we developed methods to eradicate lantana infestation and restore the landscape. However, as we learned with our experience in CTR, the ultimate success of such a program banks heavily on the conviction and motivation of stakeholders. Landscapes degraded by invasive species are often extensive, and even as weeds are eradicated from one area, the propagule pressure can persist from other areas. A well-coordinated removal program followed by restoration at suitably large scales is imperative to tilt the scales in favor of native species (D'Antonio and Meyerson 2002). A strong determination by the PA managers was crucial for the success of such a program.

The benefits of lantana eradication and subsequent restoration to grasslands in CTR are many: enhanced biological productivity, particularly in terms of palatable species of grasses and legumes; greater retention of soil moisture; prevention of soil erosion; enrichment of native biodiversity; increased frequency of wildlife sightings; and enhanced recreational values since CTR is a favorite place for ecotourists and ornithologists (Sankaran 2007) .

We anticipate that our observations on lantana management in CTR and the success of the Corbett model will help in developing a similar management strategy for other PAs, which are presently under threat of lantana and weeds like Santa Maria feverfew, bittervine, and tropical whiteweed. Any restoration program for a similar setting would also need to be informed by a variety of factors such as the dispersal mechanism of the invader, soil, climate, the present ecosystem condition, condition of neighboring ecosystems, and most importantly, the requirements of the stakeholders. As is the case with our earlier experiences on degraded landscapes in the Himalayan region (Babu et al. 1990, Jha et al. 1994, Jha et al. 1995), the present study further emphasizes that although the broader theme of restoration is applicable for any ecosystem, the approaches for restoration of degraded ecosystems are inherently site and case specific. With the mounting pressure on our natural resources, more and more ingenious methods will have to be developed to restore the ecologically depauperate landscapes created by invasive species.

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