

Pinus patula is actively progressing along the invasion trajectory in central Nepal

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Abstract

Pinus patula, a native to Mexico, was introduced for reforestation in the mid-hills of Nepal during 1960s. Initially intended for managed plantation, it is now aggressively colonizing adjoining areas, including natural forests. In this context, we assess its invasion continuum across three sites in central Nepal using the unified invasion framework. We sampled 120 plots (10 m× 10 m), with 59 in the plantation forest and 61 in the adjacent areas. Our results showed that *P. patula* population is rapidly expanding beyond plantation sites, with abundant seedlings, saplings and trees in the surrounding areas. Offspring dispersed as far as 530 meters from source populations, indicating high potential to invade natural forest ecosystems. The results suggest that this exotic tree species has successfully overcome reproductive and dispersal barriers, leading to the establishment and spread phase. These findings confirm that *P. patula* is transitioning from a 'safe' plantation species to an invasive threat, necessitating urgent containment to protect native Himalayan biodiversity and forest ecosystems.

1. Introduction

Fast growing exotic trees have been widely planted around the world for timber production, soil stabilization, fuelwood and ecosystem restoration (Zerga et al. 2021). However, hundreds of such exotic tree species have become invasive over the past few decades (Richardson and Rejmánek 2011), and some are now considered among the most impactful invasive exotic species (Lowe et al. 2000; Richardson and Rejmánek 2011). These invasive trees have substantial and increasing negative impacts on biodiversity, ecosystem structure and function, soil properties and human livelihoods (IPBES 2023; Linders et al. 2019). The study of exotic tree invasions, therefore, provides valuable insights into the processes and mechanisms underlying biological invasion (Petit et al. 2004), and the genus *Pinus* has been suggested as a model group in invasion ecology (Richardson 2006).

Pinus patula Schiede ex Schltdl. & Cham., a native to Mexican highlands, is among the most widely introduced exotic tree species (Trujillo-Miranda et al. 2021), particularly in tropical and subtropical regions of Africa, Asia, South America and Oceania for forestry, watershed management and landscape restoration (Farjon 2010; Richardson and Rejmánek 2011). However, the species has escaped from managed plantation, and become naturalized in many countries such as South Africa, New Zealand, Australia, Kenya, Uganda and parts of South America (Richardson and Rejmánek 2011), because of its aggressive regeneration and adaptability to a wide range of environmental conditions (Farjon 2010). The species has already been declared as invasive tree species in South Africa, Zimbabwe, Botswana, Malawi (Haysom and Murphy 2003), Madagascar and New Zealand (Richardson and Rejmánek 2004). In the Himalayan region, *P. patula* was initially introduced during the mid twentieth century (Jackson 1994; Singh 1982), and planted in Western (Uttarakhand, India), Central (Nepal and Darjeeling, India) and Eastern Himalaya (Bhutan and Arunachal Province, India) (Fig. 1).

Exotic tree plantation in the mid-hills of Nepal began in the 1960s, with pine species being prioritized for the plantation (Gautam and Webb 2001). During the early 1980s, nearly 0.4 million hectares of plantations were successfully established in the mid-hills of Nepal, with *P. patula* as the dominant planted *Pinus* species (DoF 2012). The primary objective of planting *P. patula* was to restore degraded forests and to provide fuelwood

and timber for domestic and industrial uses (Gilmour et al. 1990). Simultaneously, *P. patula* stand is anticipated to provide a microclimate to restore naturally occurring broad leaved species (Gilmour et al. 1990; Jackson 1994). However, our preliminary observation showed that *P. patula* has escaped from the plantation and become integrated into the local ecosystem. Therefore, the introduction of *P. patula* in Nepal has raised concerns about its establishment, expansion and potential ecological impacts.

Despite signs of ecological establishment of *P. patula* in central Nepal, there has been no objective assessment of whether the species is advancing along the invasion continuum from introduction to spread. This creates uncertainty and confusion among the concerned authorities regarding the formulation and implementation of effective management strategies for this species. Therefore, we aimed to assess the naturalization status of *P. patula* in central Nepal following the invasion framework proposed by Blackburn et al. (2011) to determine its current stage along the invasion trajectory. This study will provide a scientific basis for evidence-based management decisions and contribute to the development of informed policies on the use and management of exotic tree species in afforestation programmes in Nepal.

2. Materials and methods

2.1 Study species

Pinus patula (Family: Pinaceae) is a medium-sized tree, typically 15–30 m tall. The species can be easily recognized by its distinctive drooping needles and reddish-brown bark, which darkens to brown at maturity. The needle-like foliage leaves are usually pale green, drooping, and arranged in fascicles of 3 (occasionally up to 5), with a persistent sheath at the base. Male cones are yellowish-brown and borne in dense clusters near the base of new shoots. The woody, greyish-brown female cones occur in whorls of two to many (Farjon 2010). It is native to the highlands of Mexico and introduced to North America, Africa, Asia and Australian continents.

2.2 Study area

This study was carried out in Chaubas of Kavereplanchowk district, Sailung of Dolakha district and Lisankhupakhar of Sinduplachowk district in central Nepal (Fig. 2, Table 1). All study sites experienced massive plantation from 1978 until 1992 (Gautam and Webb 2001). The annual average temperature and precipitation of 2025 were 19.9°C and 3427.6 mm/yr respectively (weather station at Charikot, Dolakha).

Table 1
Characteristics of the study sites and the distribution of sampling plots in each site.

Study site	Community forest	Elevation (m asl)	Aspect	Forest type	Plots in plantation	Plots outside plantation	Total plots
Chaubas	Dharapani	1650–2100	South	<i>Pinus patula</i> stand	18	26	44
Sailung	Darkha–Mahabhir	1600–2000	South/East	<i>Pinus patula</i> stand mixed with subtropical broadleaved forest	18	14	32
Lisankhupakhar	Patale	2000–2300	South	Mixed stands of <i>Pinus patula</i> and <i>Pinus wallichiana</i>	23	21	44
Total	—	—	—	—	59	61	120

2.3 Methods

A total of 120 plots (10 m × 10 m each) were sampled to assess the regeneration status (number of seedlings, sapling and trees) of *P. patula* (Table 1). Within plantations, horizontal transects were established and plots were located systematically at 100 m intervals. Outside plantations, we sampled plots at regeneration sites because *P. patula* was patchily distributed beyond plantation areas. We recorded the number of seedlings, saplings and trees in both plantation and outside plantation plots. Seedlings were defined as stems less than 2.5 cm diameter, saplings as stems between 2.5 cm to 9.9 cm DBH and trees as stems greater than 10 cm DBH with crowns fully extended into the canopy (Connell and Green 2000). We calculated the spatial distance between the source population (from the edge of the plantation) and newly established populations using plot coordinates in Geographical Information System (GIS) software to measure the dispersal distance. We applied the unified framework for biological invasions proposed by Blackburn et al. (2011) to evaluate the invasion trajectory of *P. patula*. This framework divides the invasion process into sequential stages (Transportation, Introduction, Establishment and Spread), each separated by barriers (Geography, Cultivation, Survival, Reproduction, Dispersal and Environmental) that species must overcome to progress from transportation to spread.

3. Results

3.1 Population structure of *Pinus patula*

The population structure of *Pinus patula* varied between plantation forests and outside plantations across the study sites (Fig. 3). Overall, the mean density of seedlings (582 stem/ha), saplings (322 stem/ha), and trees (475 stem/ha) were higher in plots outside plantations compared to the plantations (296 stem/ha, 77 stem/ha, and 341 stem/ha, respectively).

Site-specific analyses, however, showed distinct patterns of population structure of *P. patula*. In Chaubas, the density of saplings (396 stem/ha) and trees (748 stem/ha) outside plantations were higher than in plantations (94 stem/ha and 464 stem/ha, respectively; Fig. 3b). However, seedling density was higher in plantations (241 stem/ha) than outside plantations (48 stem/ha). In Sailung, seedling density was higher in plantations (526 stem/ha) than in outside plantations (285 stem/ha). However, sapling density was higher in outside plantations (269 stem/ha) than in plantations (147 stem/ha). Tree density did not show considerable differences between plantations and outside plantations (Fig. 3c). Lisankhupakhar provides the most robust evidence of recruitment and colonization of *P. patula* outside plantations (Fig. 3d), with very high seedlings density (1413 stem/ha) compared to plantations (140 stem/ha). A similar pattern was observed in sapling recruitment, where outside plantations had a mean of 263 stem/ha saplings compared to 4 stem/ha in plantations. In contrast, plantations exhibited higher tree density (350 stem/ha) than in outside plantations (259 stem/ha).

3.2 Dispersal of *Pinus patula*

The dispersal of *Pinus patula* into adjacent areas exhibited distinct spatial and directional patterns among the study sites (Fig. 4), highlighting the contribution of site-specific factors for its active expansion from the source population. The least dispersal was observed in Lisankhupakhar, with individuals reaching a maximum distance of about 200 m towards the east and south-east direction. A similar south-eastern dispersal trend was observed in Sailung, where the furthest established population was recorded at 265 m from the margin of plantation. The most extensive dispersal occurred in Chaubas, the furthest distant colonized was recorded at 530 m from the source population in a south-southwestern direction. Most of the population in Chaubas were established beyond 200 m from the source population, while colonization extended at least 100 m in all studied sites (Fig. 4), providing robust evidence for medium-distance dispersal and colonization of the species.

3.3 Trajectory of invasion stages

Our field observations showed that the species has established self-sustaining populations outside plantations. Seedlings, saplings and trees were abundant in degraded areas (such as roadsides) and abandoned agricultural terraces, which provide clear evidence of natural regeneration of *P. patula* beyond plantation boundaries. The invasion process has progressed to the spread stage, as evidenced by the distribution of individuals that have successfully regenerated and colonized across varied habitats (Table 2).

Table 2

Pinus patula invasion trajectory was drawn onto the unified framework proposed by Blackburn et al. (2011)

Stage	Barrier	Framework Category	Terminology	Our Observation	Trajectory Status
Transport	Geography	A→ B1/B2/B3	Exotic (introduced)	Species introduced by Australian project; planted widely in mid-hills of Nepal	Completed
Introduction	Captivity/ Cultivation	B1, B2	Plantation/ Introduced	Planted in mid hills of central Nepal; individuals observed outside plantation boundaries	Completed
Establishment	Survival	C0 → C1	Surviving exotics	Seedlings and saplings survive in fallow lands and terrace edges near plantations	Completed
	Reproduction	C2 → C3	Naturalized/ Established	Natural regeneration confirmed; self-sustaining populations outside plantations	Completed
Spread	Dispersal	D1 → D2	Spreading exotics	Individuals recorded > 500 m from plantation edges; directional spread outside plantation	Completed
	Environmental	E	Invasive	Colonizing varied habitats (fallow lands and agricultural margins); crossing environmental barrier	In progress

4. Discussions

Biological invasion process has four major stages from transportation of exotic species to spread of the species after successful establishment in a novel environment (Blackburn et al. 2011). Exotic species that become naturalised in a new ecosystem, spread and negatively impact biodiversity, local ecosystems or native species are considered invasive species (IPBES 2023; Roy et al. 2024). *Pinus. patula* has invaded natural and semi-natural ecosystems by outcompeting understory flora in some African countries and in New Zealand where the species has been categorised as invasive (Baohanta et al. 2012; Haysom and Murphy 2003). However, invasions are context-specific and need to be evaluated based on species identity, establishment, dispersal potential, regeneration and environmental impact to develop a mechanistic understanding of the outcome of species introductions (Blackburn et al. 2011; IPBES 2023). We observed that *P. patula* has overcome the barriers of geography, survival, and reproduction, and has now established self-sustaining populations outside its intended plantation boundaries in central Nepal. The species had

maximum survival rate compared to other Pine species and appeared to be invasive for local flora in Western Himalaya (Bhattacharyya et al. 2010).

Our study showed that the reproductive individuals were present at significant distances from source plantations, confirming that the species has already entered the 'Spread' stage, specifically category D2 (Blackburn et al. 2011). This categorization is further supported by presence of abundant seedlings, saplings and trees outside plantation compared to the plantation forests. The high seedling and sapling density outside plantation boundaries indicate that environmental barriers to establishment have been mostly overcome (Peláez et al. 2020), and the species is actively progressing toward becoming 'invasive' (Category E) across the region. Therefore, *P. patula* has successfully transitioned from a managed plantation species to a naturalized and actively spreading exotic species in central Nepal.

This study underscores the need to address the invasion debt created by decades of *Pinus. patula* plantation in central Nepal. Since the species has already crossed stage D2 and is progressing towards becoming invasive, there is a critical window of opportunity for eradication, particularly for smaller, isolated populations. It is because early detection and rapid response remain the most effective way for managing invasive alien species (Hulme 2006). Lessons from some African countries have suggested that unchecked regeneration has increased propagule pressure and has raised concerns for restoration efforts (Lockwood et al. 2005). In this context, prioritizing *P.patula* for reforestation may increase invasion risk in the landscape, while the persistence of monoculture stands could limit ecosystem resilience. Therefore, gradually replacing *P. patula* stands with native broadleaved tree species through restoration programme can reduce invasion risks while maintaining ecosystem functions (Stelstra 2021). De-prioritization and ultimate ban on this species for plantation forestry can reduce its propagule pressure and invasion risks to natural ecosystems including forests in the Himalaya.

5. Conclusions

The current status of naturalization and the spread of *Pinus. patula* in central Nepal emphasize the importance of assessing the invasion risks of exotic trees before their large-scale plantations. Current practices of propagating exotic tree species (such as *P. patula*, *Tectona grandis*) in the government and private nurseries and prioritizing them in afforestation and reforestation without risk assessment, may increase invasion risk at the landscape level across the Himalayas. This study provides evidence of naturalization of a widely planted exotic tree, *P. patula*, and highlights the importance of assessing exotic species before plantation, as well as conducting regular monitoring of such species in plantation forests. Considering Nepal's commitments under the Convention on Biological Diversity (CBD) and Target 6 of the Kunming–Montreal Global Biodiversity Framework, proactive containment of *P. patula* is urgently required to prevent further spread and potential ecological damage. Future research is recommended to quantify the impact of *P. patula* on the native ecosystems, providing evidence to guide management of the Himalayan landscape.

Declarations

Competing Interests

The authors have declared that no competing interests exist.

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Author Contributions

PB, LNS, and BBS contributed to the study conception and design. PB, SB and MK were involved in data collection. PB performed the analysis and prepared the first draft of the manuscript, and all authors commented on previous versions. All authors read and approved the final manuscript.

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Figures

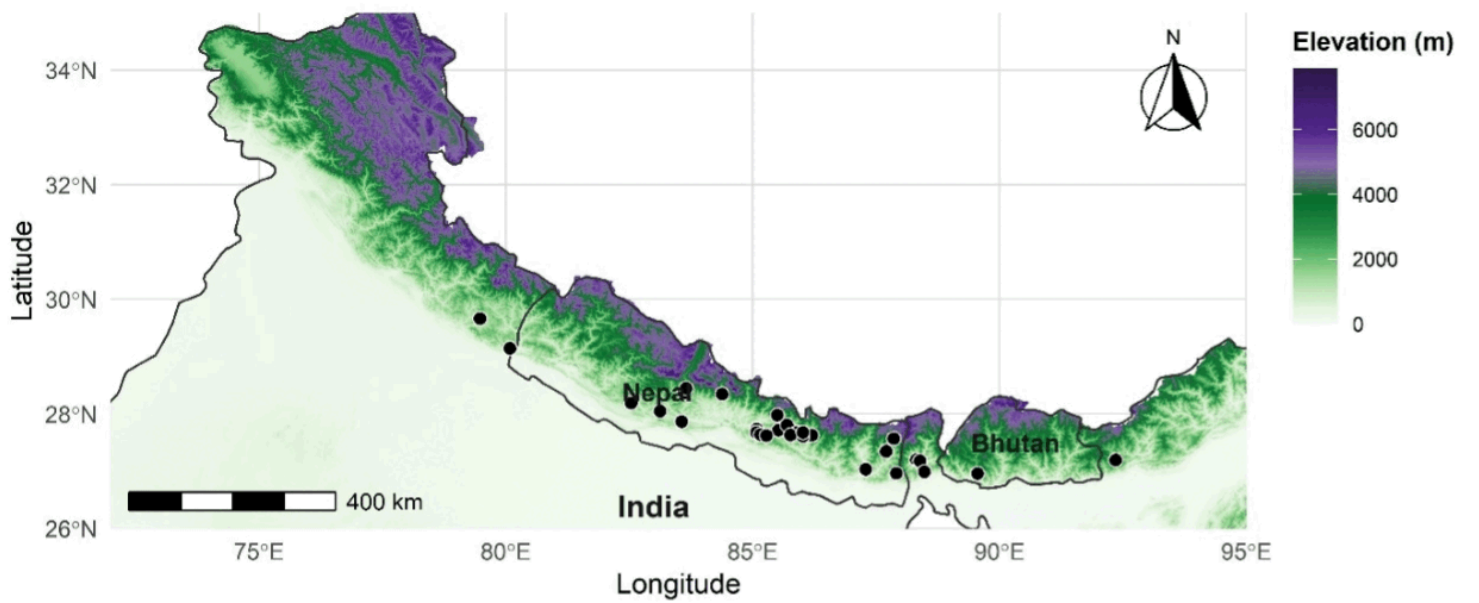


Figure 1
Map showing plantation locations (black dots) of *Pinus patula* in the Himalayan region.

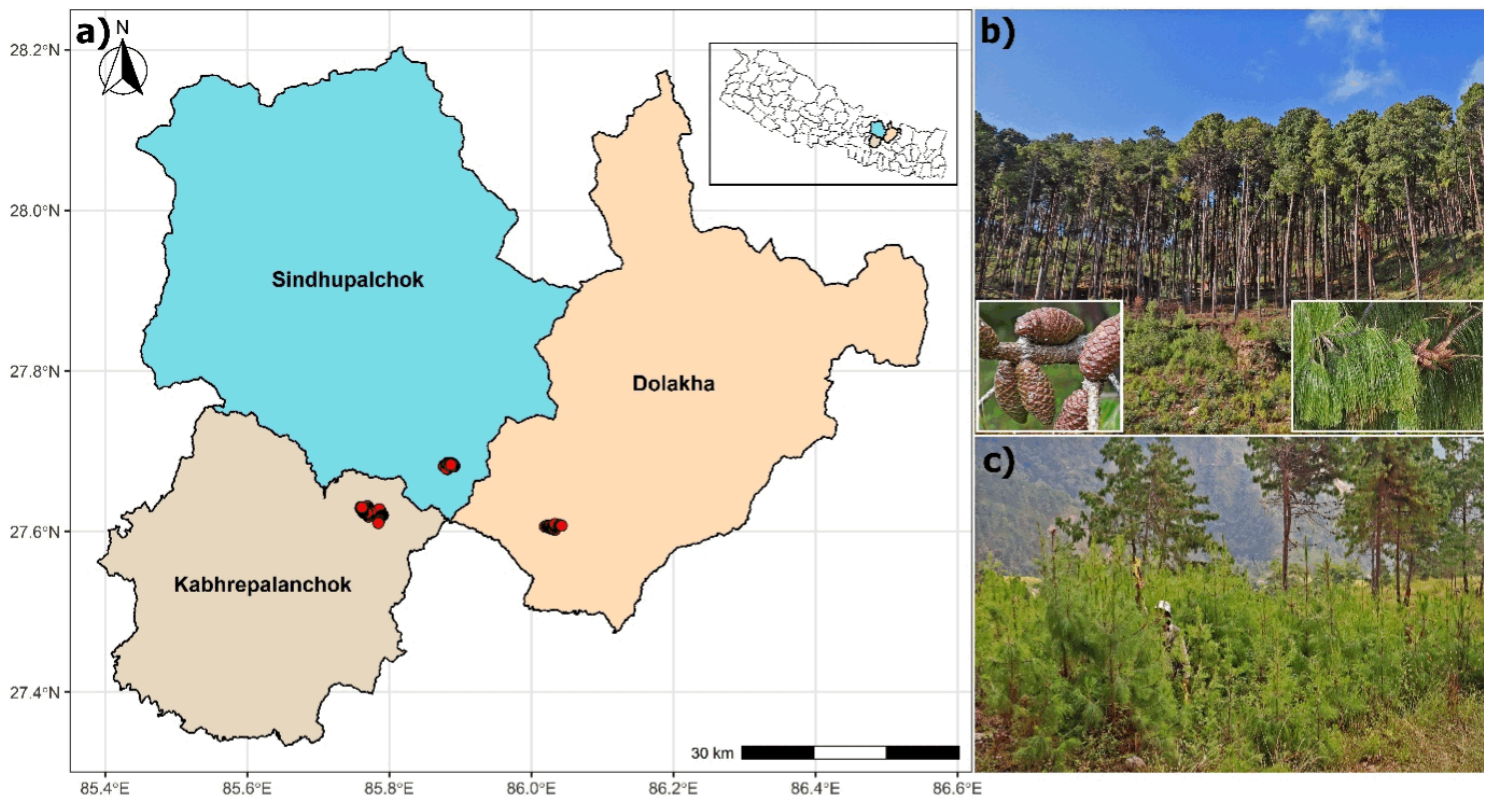


Figure 2

a) Map showing location of sampling plots (red dots) in three districts, b) *Pinus patula* plantation forest with leaves and male cones, c) Dense regeneration stand of *Pinus patula* outside plantations.

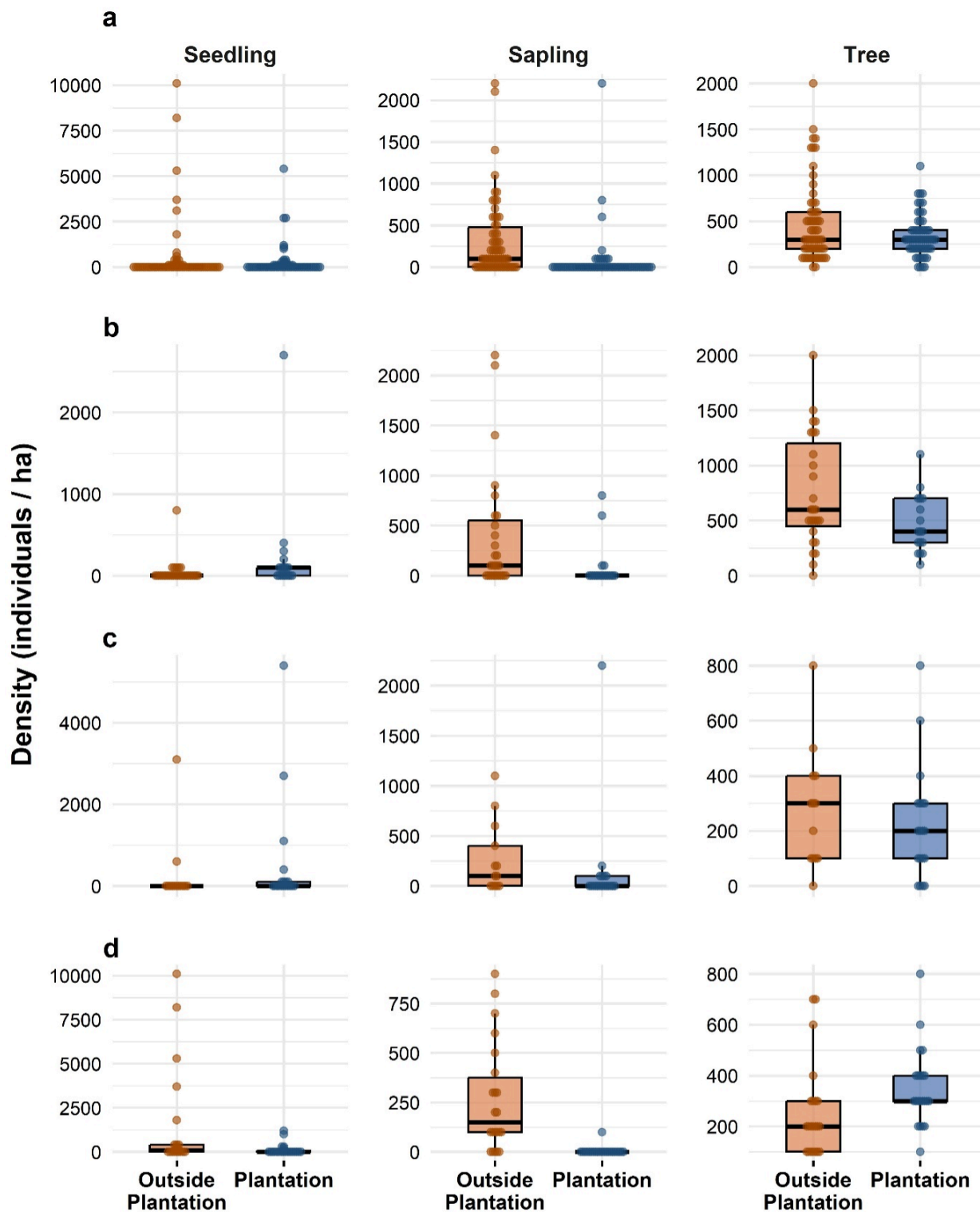


Figure 3

Boxplots showing the density of *Pinus patula* across developmental stages (seedlings, saplings, and trees) in plantation and outside plantation, (a) data pooled across all study sites, (b), (c) and (d) present the results for Chaubas, Sailung, and Lisankhupakhar, respectively.

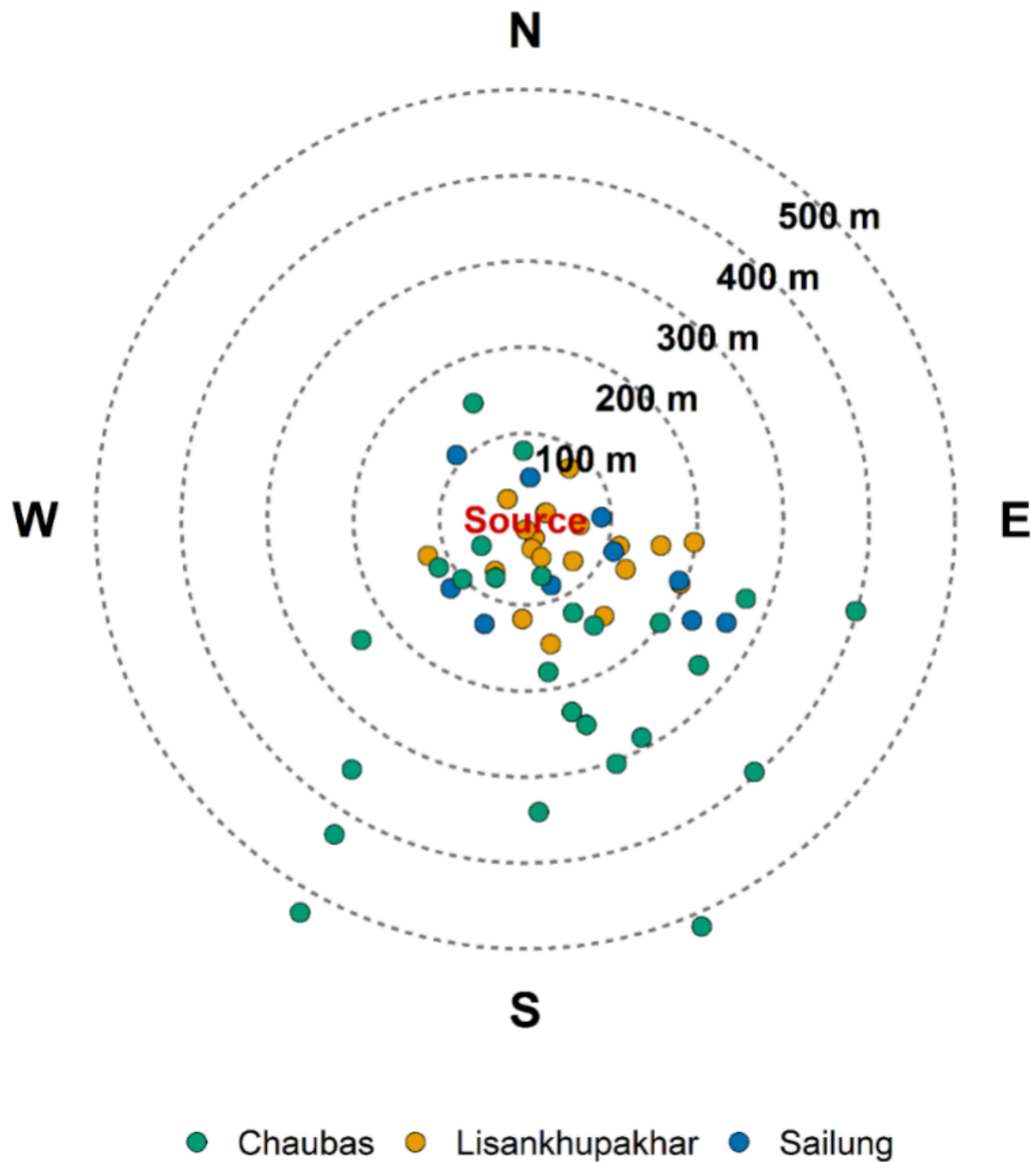


Figure 4

The figure illustrates the spatial distance and direction of regeneration of *Pinus patula* from the plantation source. The dashed concentric circles indicate distances from the source. Coloured points represent regenerated population in colonized areas in Chaubas (green), Lisankhupakhar (orange), and Sailung (blue).