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ORIGINAL ARTICLE

Invasion driven changes in soil nutrient dynamics by *Conyza Canadensis* (L.) in the Kashmir Himalaya

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ABSTRACT

Biological invasions are major drivers of ecological change, often altering soil nutrient cycling and ecosystem functioning. This study investigated the effects of the invasive alien plant *Conyza canadensis* on soil properties and nutrient dynamics across several sites in the Kashmir Himalaya. At each site, paired invaded (IN) and uninvaded (UN) plots with comparable environmental conditions were selected. Soil samples were analyzed for physicochemical properties and nutrient concentrations. Significant differences ($P < 0.05$) were observed between invaded and uninvaded plots for all measured soil variables across the study sites. Invaded plots exhibited significantly higher soil pH, organic carbon, and total nitrogen, whereas electrical conductivity, available phosphorus, and micronutrients, including iron, copper, manganese, and zinc, were significantly lower. These patterns were consistent across all sampled locations, indicating a strong influence of *C. canadensis* on soil conditions. Principal Component Analysis further demonstrated clear differences in soil nutrient composition between invaded and uninvaded plots. The findings indicate that *C. canadensis* substantially modifies soil properties and nutrient availability, potentially altering nutrient pools and biogeochemical processes in invaded habitats. Such changes may promote positive plant–soil feedbacks that enhance the establishment and persistence of the invader. Effective management of *C. canadensis*, together with restoration of altered soil conditions, is therefore essential for conserving native ecosystem integrity in the Kashmir Himalaya.

KEYWORDS

Biological invasion; *Conyza canadensis*; Kashmir Himalaya; Soil nutrient dynamics; Organic carbon; Total nitrogen; Plant–soil interactions

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Introduction

Biological invasions are widely recognized as one of the most significant drivers of global environmental change, ranking alongside land use transformation, climate change, and pollution in their capacity to threaten biodiversity and ecosystem functioning [1,2]. Among the various forms of biological invasions, the spread of invasive alien plants has attracted particular attention because of their profound influence on native communities and ecosystem processes. These species frequently establish dense populations that outcompete native vegetation, resulting in the displacement of resident species and associated biota. Such changes often lead to reduced species diversity, altered community composition, and increased ecological homogenization of invaded landscapes [3–6]. While the above ground impacts of plant invasions are often readily apparent, their effects on below ground are less visible but can be equally, if not more, consequential. Invasive plants can substantially modify the physical, chemical, and biological properties of soils, thereby influencing ecosystem processes that persist long after the invader has been removed [7–9]. Such alterations may create legacy effects that impede the recovery of native plant communities and complicate restoration efforts. Evidence from global syntheses indicates that invasive plants frequently enhance soil biochemical activity. For instance, plant invasions increase the activity of nutrient cycling enzymes by 23–69%, potentially promoting conditions that facilitate further invasion [10]. Similarly, invasive plants can exert positive effects on several soil attributes, including soil pH, organic carbon, total and available nitrogen and phosphorus, microbial biomass, and the diversity of bacterial and fungal communities [11]. Collectively, these findings highlight the capacity of invasive plants to modify soil environments in ways that may reinforce their establishment and persistence within invaded ecosystems.

It is well established that invasive species significantly affect soil system dynamics. These effects range from changes in the cycling of crucial elements like nitrogen, carbon, and other nutrient pools to modifications of the physiochemical properties of the soil, such as moisture, pH, organic matter, temperature, and microbial activity [12–16]. Although the consensus in current literature points to an increase in soil nutrient pools driven by plant invasions [15,17,18], this trend is not universal, as some researchers have documented notable declines instead [19,20]. As a result, the effects of alien plant species on areas they have colonised are unique to each invader [21,22]. Furthermore, the effects of invasive species differ greatly depending on the local conditions and the specific site [21–23]. In a cold, arid desert, for instance, *Bromus tectorum* invasion speeds up mineralization and nitrification, but in warm, arid grasslands, it exhibits the opposite trend [24,25]. This fact has led to the proposal that species and site specific contexts be used to investigate the effects of invasive species [21,26]. By altering soil chemistry and hydrology, invasive plants make it more challenging for native plants to grow. Some invasive species modify the pH of soils, alter nutrient cycling, while others change fire regimes [27], leading to alterations in the productivity of plant communities [28,29]. For instance, certain invasive plants can fix nitrogen, leading to changes in the availability of this nutrient for other plants. Overall, invasive plants can significantly impact net primary productivity, leading to a decline in the productivity of native plant communities and altering ecosystem dynamics, which can result in a decline in biodiversity and changes to the ecosystem services provided.

In recent years, mountains are thought of as the ideal natural laboratory for investigating how changing climatic conditions affect an ecosystem's overall functioning [30].

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Although plant invasions are less prevalent in the mountain ecosystems than in low land habitats, some invasive plants are nonetheless present [31]. There is an urgent need to understand the distribution patterns and underlying mechanisms driving these invasions, particularly regarding how they affect mountain soil nutrient pools. Kashmir, a region in the northwest of the Indian Himalayas, is thought to be ecologically vulnerable, yet serves as a concentrated biological reservoir [32]. While occupying barely 2.15% of the Himalayan territory, the region is home to over 2000 plant species, amounting to 20% of the entire mountain range's floral diversity [33]. The alien flora of the Kashmir Himalaya has been found to contain 571 plant species, including 96 invasive species [34]. Studies have also shown a significant correlation between *C. canadensis* density and soil properties [35] with emerging evidence linking its herbicide resistance directly to the biotic components present in the soil [36]. Due to its association with arbuscular mycorrhizal mutualists, it has been acknowledged that it affects belowground processes [37]. Despite these insights, the exact feedback loops between this weed, soil nutrient cycling, and its associated microbial communities remain poorly understood. Furthermore, no research to date has investigated how this invasive plant impacts belowground soil system dynamics specifically within the Kashmir Himalayan region. Based on this context, this study investigates the impacts of *C. canadensis* invasion on the soil nutrient dynamics in the habitats of Kashmir Himalaya.

Materials and methods

Study area

The work was carried out in the Kashmir region, a distinctive biogeographical area situated in the Indian Himalayas [38]. Encompassing an area of 15,978 square kilometres [33], the region is geographically bounded by coordinates 32 ◦ 20′ and 34 ◦ 54′ N latitude and 73 ◦ 55′ and 75 ◦ 35′ E longitude [39]. Mountainous terrain dominates roughly 64% of the landscape [34], forming a deep, oval valley enclosed by the Zanskar range of Greater Himalaya to the north and north east and Pir Panjal range of the Lesser Himalaya in the south and southwest [32]. The area is mainly characterised by continental temperate climate, with temperatures fluctuating between − 4 ◦ C in the winter to 31 ◦ C in the summer (diurnal ranges: −4°C to 4°C in winter; 15°C to 31°C in summer). The region receives a mean annual precipitation of 1055 mm, primarily occurring as snowfall during the winter. Coniferous forests and alpine meadows are the primary vegetation types [40], anchoring soils that are predominantly loamy textured [41].

Sampling sites

Table 1. Location of the sampling sites for Conyza canadensis.

Sites	Site name	Altitude (m)	Coordinates
Site 1	Hazratbal	1550	34°07′ 07″ N, 74° 50′05″ E
Site 2	Budgam	1600	33°57′36″ N, 74° 49′14″ E
Site 3	Pampore	1600	33°58′ 59″ N, 74° 56′29″ E
Site 4	Ganderbal	1600	34°13′ 25″ N, 74° 46′18″ E
Site 5	Bandipora	1650	34° 26′01″ N, 75°35′01″ E

The study area was extensively surveyed to determine the distribution of *C. canadensis.* The result of these surveys did not show any significant elevational differences among the *C. canadensis* sites. Therefore, we selected sites located in the plains, each 10 kilometres apart from one another (Table 1).

Sampling design

The current study adhered to the Global Invader Impact Network's methodology [21]. Two different kinds of sampling plots were chosen at each site: [1] plots that were invaded (IN) by the target invasive plant and [2] plots that were not invaded (UN), which were geographically isolated and outside the invaded area but had comparable environmental conditions withe target invasive plant absent. Within each of the two types of sample plots, 1 × 1 m quadrats with ten replicates of were laid out. It was made sure that the different types of sampling plots (IN and UN) at each chosen site had similar environmental characteristics (such as vegetation, aspect, slope, and land use history), but that they differed based on whether the target invasive plant was present or not. The criterion was used to make sure there was no clear reason, other than dispersal constraints, why the invader was not present [15].

Soil sampling

Soil sampling was conducted were taken when the vegetation was at its peak. At each quadrat, five sub samples (one at the centre and four at the corners) were randomly collected at a depth of 15 cm using a standard 2.25 cm diameter soil corer. The subsamples were well mixed, collected in polythene bags, and stored at -4 °C. In the laboratory, fresh soil samples were manually crumbled to separate the soil aggregates. The broken up soil was then allowed to air dry before being sieved through a sieve of 2 mm pore size to eliminate any remaining debris. After that, the soil samples were kept in a refrigerator at -4 °C until they could be examined further.

Soil analysis

Soil analyses were conducted at the Soil Science Division of the Department of Agriculture (Lal Mandi, Srinagar) and soil testing laboratory of the Department of Horticulture (Rajbagh, Srinagar). A digital pH metre (LI 614 model, Elico Ltd., Hyderabad, India) was used to measure the pH of the soil using a slurry of soil and distilled water (1:2.5 w: v). The pH metre was calibrated using standard buffer solutions with a pH of 4 and 7 prior to analysis. The electrical conductivity (EC) of the soil was determined using a digital conductivity meter (model No. CM 183 ECTDS, Elico Corp. Ltd., Hyderabad, India). The soil organic carbon (OC) was determined by the fast titration method of Walkley and Black, the Kjeldahl method (1883) was used for total nitrogen (N), and for available phosphorous (P) [42–44].

Data analysis

Before performing variance analysis, the data were visually examined for normalisation using a Q-Q plot (quantile–quantile plot) to determine the homogeneity of variances, or the strength of the data distribution, when the sample size exceeded twenty. This was done by employing the central limit theorem. A log transformation was applied when the data was not regularly distributed. Soil nutrient variables were analysed using a two way ANOVA (Analysis of Variance) with invasion status, site, and their interaction as main effects (soil nutrient variables ~ Status + Sites + Status: Sites) to compare means and identify any correlations between the variables. This was done using IBM SPSS Statistics, Version 23. The P values for

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several pairwise comparisons were adjusted using the Bonferroni multiple testing correction technique. As a result of the smaller group comparison (un-invaded Vs invaded plots) of the study, Bonferroni's predictive power outperformed the other methods. Using the corr.test() function in the "corrplot" package, Pearson's coefficient of correlation was computed for IN or UN plots to examine the link between different soil parameters throughout the study locations (Wilke, 2017). Using the "factoextra," "FactoMineR," and "ggbiplot" packages, Principal Component Analysis (PCA) was used to determine the significant soil factors associated with various IN and UN plots [45]. All statistical computations and visualisations were performed using the R statistical language [46].

Results

It is considered that plant invasion significantly affects the characteristics of soil. Analysis of variance (ANOVA) revealed that majority of the soil properties varied significant ($p < 0.05$) across study sites, invasion status, and their corresponding (status × site) interactions (Table 2). In comparison to the nearby un-invaded plots, we found that the majority of the soil parameters in the *C. canadensis* invaded plots had significantly ($p < 0.05$) higher values.

Table 2. ANOVA results showing the effects of Conyza canadensis invasion status, site and their interactions on soil parameters.

Parameters	Factor	Sum of square	d*f*	Mean square	F-value	Sig
pH	Sites	.559	4	.140	1.741	.181
	Invasion status	7.086	1	7.086	88.331	.181
	Sites **x** Invasion status	.421	4	.105	1.312	.300
Electrical conductivity	Sites	122.467	4	30.617	2.783	.116
	Invasion status	5992.533	1	5992.533	415.187	.000
	Sites **x** Invasion status	11.133	4	2.783	.193	.939
Total nitrogen	Sites	.038	4	.010	29.184	.000
	Invasion status	.218	1	.218	668.735	.000
	Sites **x** Invasion status	.006	4	.001	4.551	.009
Organic carbon	Sites	.474	4	.119	123.102	.000
	Invasion status	13.214	1	13.214	13716.543	.000
	Sites **x** Invasion status	.475	4	.119	123.144	.000
Phosphorus	Sites	40.943	4	10.236	36.990	.000
	Invasion status	931.416	1	931.416	3365.954	.000
	Sites **x** Invasion status	90.815	4	22.704	82.047	.000
Iron	Sites	.066	4	.017	8.233	.000
	Invasion status	38.829	1	38.829	19349.782	.000
	Sites **x** Invasion status	.004	4	.001	.443	.776
Manganese	Sites	.015	4	.004	3.115	.038
	Invasion status	8.237	1	8.237	7020.409	.000
	Sites **x** Invasion status	.017	4	.004	3.612	.023
Copper	Sites	.551	4	.138	23.881	.000
	Invasion status	6.422	1	6.422	1113.609	.000
	Sites **x** Invasion status	.620	4	.155	26.875	.000
Zinc	Sites	.093	4	.023	.497	.738
	Invasion status	.300	1	.300	6.433	.020
	Sites **x** Invasion status	.145	4	.036	.775	.554

Soil property dynamics across invaded and un-invaded plots of *C. canadensis*

The soil pH and EC exhibited highly significant differences between the IN and UN plots across all sampling sites ($p < 0.001$), (Table 2). The pH values were elevated in the IN plots, compared to the uninvaded counter parts, whereas EC exhibited the inverse trend (Figure 1, Figure 2). Moreover, the site-specific analyses confirmed that the variations in soil pH and EC between the IN and UN soils remained uniform across all study sites (Figure 1). Significant differences across all the sampling sites, when comparing soil macronutrients between IN and UN plots was observed. Most prominently, the concentrations of soil organic carbon (OC), total nitrogen (N), and available phosphorus exhibited highly significant shifts between the IN and UN soils at all the sampling sites ($p < 0.0001$) (Table 2). The values of N and OC were higher in the IN soils, compared to UN soils across all sites, while as phosphorus has shown the opposite trend (Figure 2). Site wise analysis revealed that difference in OC, N, and phosphorus between IN and UN plots was consistent at all sites. The values

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of all the micronutrients under study, viz. Fe, Mn, Cu and Zn, exhibited a notable decline in concentration in the IN soils compared to UN soils across all the sites (Figure 1). There exist significant differences between IN and UN plots at all sites ($p < 0.001$) except for zinc which didn't show any significant difference at site 3 and 4 ($p > 0.05$) (Figure 1, Table 3).

Table 3. : Mann–Whitney U test results comparing soil properties between *Conyza Canadensis* invaded and uninvaded plots across all sampling sites. Values represent mean $\pm$ standard deviation (in parentheses)

Sites	Site 1		Site 2		Site 3		Site 4		Site 5	
	IN (n=10)	UN(n=10)	IN (n=10)	UN (n=10)	IN (n=10)	UN (n=10)	IN(n=10)	UN(n=10)	IN (n=10)	UN (n=10)
pH	8.78 (±0.63)	7.58*** (±0.23)	8.64 (±0.52)	7.4*** (±0.57)	8.45 (±0.77)	7.53** (±0.46)	8.32 (±0.95)	7.74** (±0.96)	8.82 (±0.73)	7.89*** (±0.77)
EC (µs/cm)	182.33 (±9.45)	209.6*** (±6.45)	178.33 (±12.02)	208** (±13.21)	180.66 (±12.84)	208.66* (±17.20)	176 (±15.1)	205.66* (±22.40)	183 (±16.15)	209.6* (±13.3)
N (%)	0.33 (±0.05)	0.12 *** (±0.01)	0.32 (±0.02)	0.136*** (±0.008)	0.4 (±0.07)	0.25*** (±0.05)	0.35 (±0.03)	0.2*** (±0.03)	0.33 (±0.017)	0.17*** (±0.01)
OC (%)	2.91 (±0.28)	1.32*** (±0.17)	2.89 (±0.35)	1.4*** (±0.25)	2.82 (±0.12)	1.51*** (±0.25)	2.7 (±0.25)	1.31*** (±0.15)	2.26 (±0.08)	1.4*** (±0.11)
P (kg/h)	16.05 (±1.58)	25.84 (±1.98)	15.08 (±1.76)	24.47 (±1.86)	14.37 (±1.82)	24.16 (±1.67)	15.91 (±0.91)	24.6 (±0.95)	13.6 (±0.52)	31.66 (±1.98)
Fe (ppm)	0.76 (±0.057)	3.06*** (±0.31)	0.87 (±0.08)	3.11*** (±0.2)	0.81 (±0.06)	3.1*** (±0.15)	0.86 (±0.05)	3.15*** (±0.09)	0.92 (±0.07)	3.18*** (±0.2)
Mn (ppm)	0.42 (±0.01)	1.45*** (±0.15)	0.45 (±0.02)	1.51*** (±0.12)	0.41 (±0.08)	1.47*** (±0.07)	0.38 (±0.04)	1.5*** (±0.04)	0.43 (±0.02)	1.4*** (±0.05)
Cu (ppm)	0.86 (±0.01)	1.84*** (±0.09)	0.84 (±0.07)	1.24*** (±0.02)	0.85 (±0.08)	1.77*** (±0.1)	0.76 (±0.06)	2.03** (±0.42)	0.89 (±0.09)	1.94*** (±0.08)
Zn (ppm)	0.11 (±0.003)	0.45*** (±0.06)	0.14 (±0.01)	0.42*** (±0.03)	0.38 (±0.02)	0.41^{ns} (±0.01)	0.39 (±0.02)	0.42^{ns} (±0.02)	0.13 (±0.008)	0.46*** (±0.03)

IN represents invaded and UN represents uninvaded regions.

Significance levels: $p < 0.05$, *p < 0.01, ***p < 0.001.
ns stands for not significant with $p > 0.05$

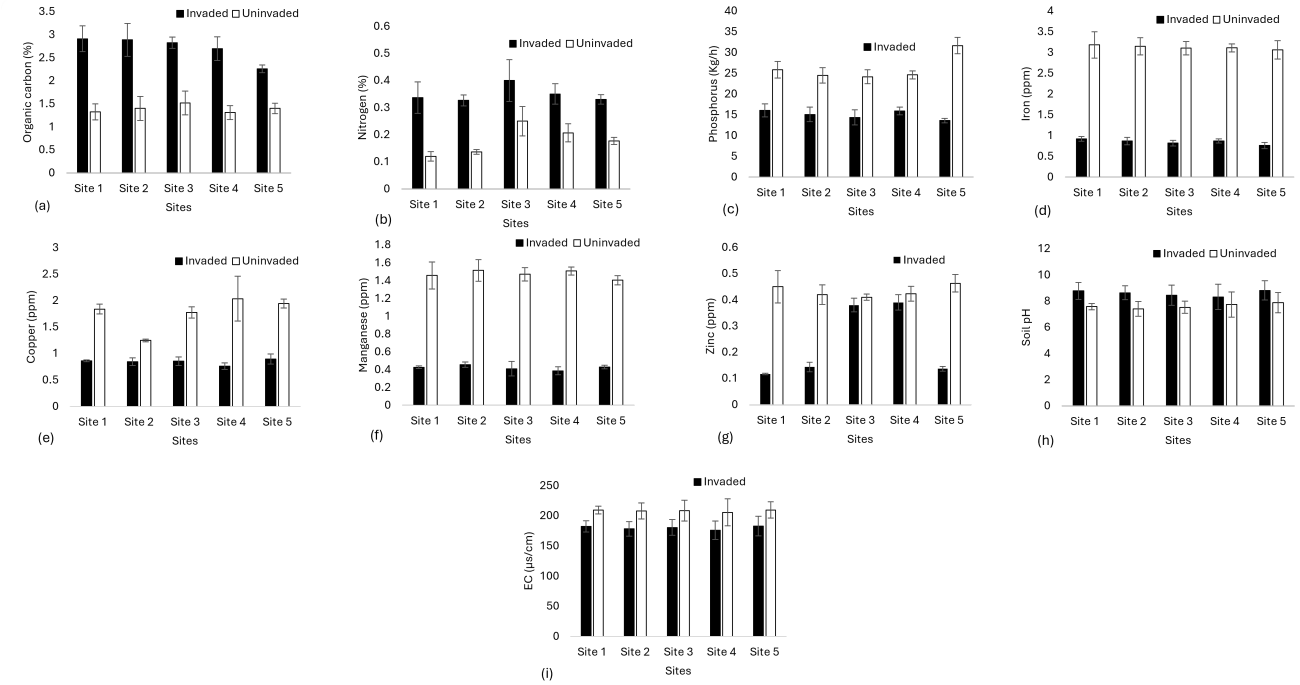


Figure 1. Differences in soil chemical properties (nutrients) between C. canadensis invaded (black bars) and un-invaded (white bars) plots at different sites

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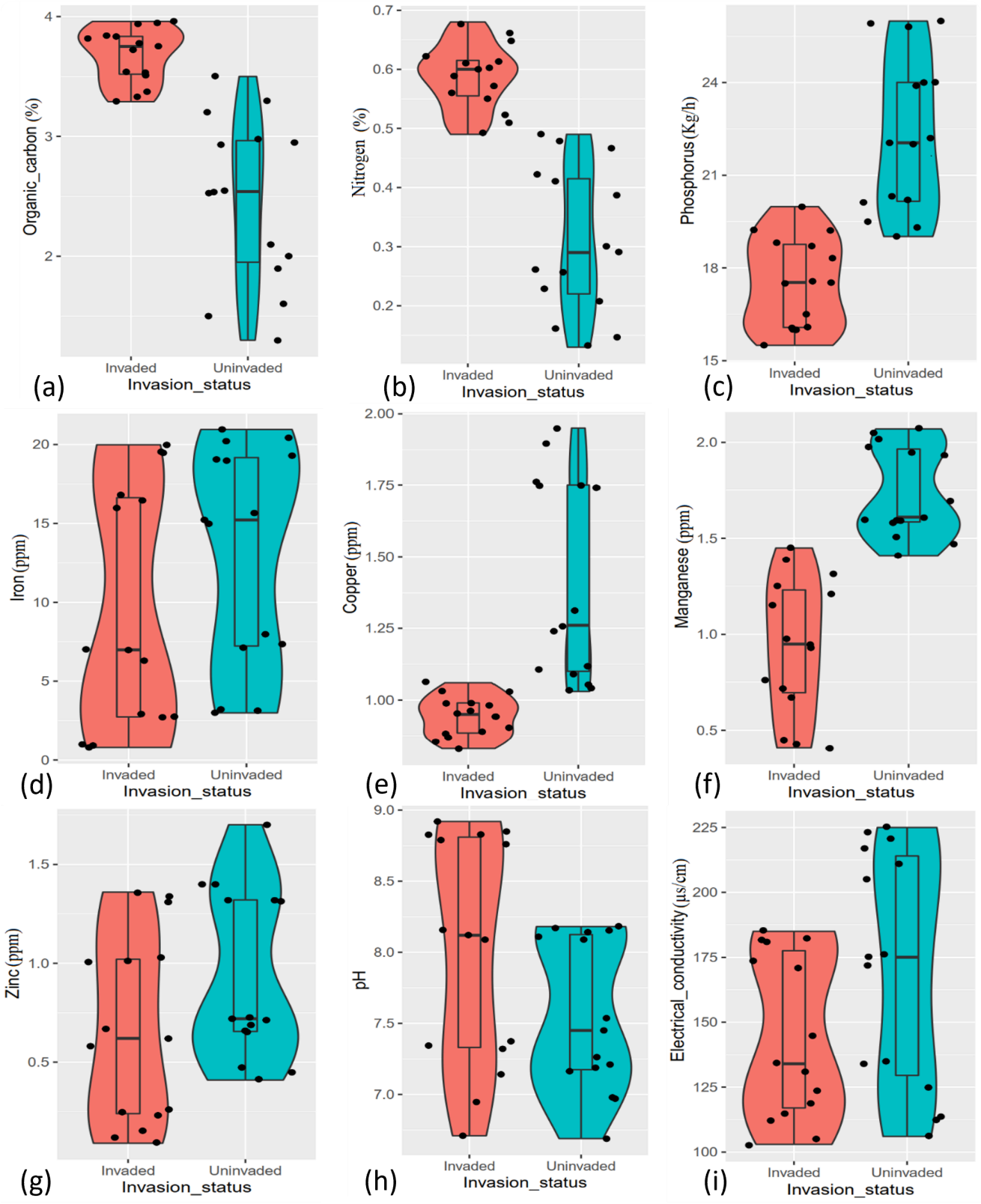


Figure 2. Violin plot comparing the parameters of soil between IN and UN plots of *Conyza canadensis* within the Kashmir Himalaya. The shape in a violin plot, represents the probability density of the data at 95% confidence interval. The average value is displayed by the black line inside the box plot, and the extreme values are displayed by the black circles.

Correlation analysis

Pearson's correlation analysis of the soil variables indicated that the majority of variables exhibited no significant correlation with one another (Figure 3). In the invaded plots

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soil EC exhibited negative correlation only with Zn (r = −0.60; p < 0.05) and positive correlation with pH (r = 0.56; p < 0.05) while with other soil variables EC non-significant correlation. pH was positively correlated with copper (r = 0.55; p < 0.05). Phosphorus negatively correlated with Cu (r = −0.56; p < 0.05) and positively correlated with OC and Fe (r = 0.65 and 0.85 respectively; p < 0.01). OC was positively correlated with Fe (r = 0.77; p < 0.001). In the uninvaded plots EC didn't show significant correlation with any soil variable. pH was positively correlated with Zn and P (r = 0.74; p < 0.01, and r = 0.60; p < 0.05 respectively) and negatively correlated with N (r = −0.75; p < 0.01). Nitrogen was positively correlated with OC (r = 0.54; p < 0.05) and negatively correlated with Fe (r = −0.51; p < 0.05). Phosphorus was positively correlated with Zn (r = 0.72; p < 0.01) and negatively correlated with Mn (r = −0.74; p < 0.01). Rest of the interactions between soil variables were not significant.

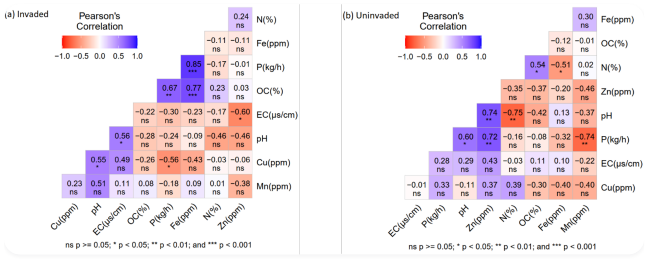


Figure 3. Pearson's correlation matrix illustrating the relationships between different soil chemical parameters at a) invaded, and b) uninvaded plots Conyza canadensis. The colour gradient reflects the strength of the correlation; blue represents positive relationship and red represents negative correlations.

Principal component analysis

PC1 and PC2 contributed 46% and 10.2% respectively, which collectively constituted ~ 56% variability in the overall soil properties, independent of whether the plots were invaded or uninvaded (Figure 4a). Furthermore, two distinct eclipses were observed for the IN and UN plots (Figure 4b). Soil micronutrients, EC and P content served as the primary drivers in the UN plots, while OC, N, and pH became the defining variables in *C. canadensis*–IN plots (Figure 4b).

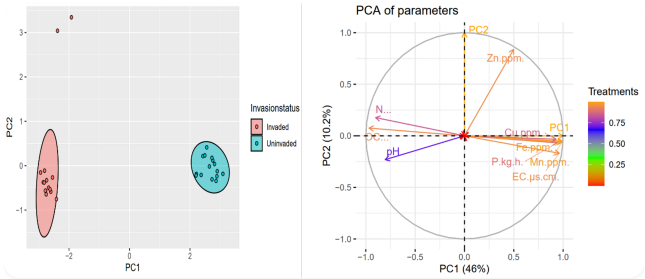


Figure 4. The PCA biplots illustrating soil chemical dynamics in *Conyza canadensis* habitats a) panel (a) variation across study sites, and b) comparison between invaded and un-invaded plots.

Discussion

In the backdrop of modern globalisation, Human footprints are restructuring the wild. By carving up natural landscapes, overexploiting native wildlife, and opening the floodgates to global tourism, we have unintentionally rolled out the red carpet for invasive species to take over. The outcome of this introduction doesn't stop at the surface, they fundamentally shift the dynamics of soil nutrients that sustain fragile mountain ecosystems [47]. The present study revealed that the impact of invasion by *C. canadensis* on overall soil properties is both substantial and highly localised, because the impact heavily depends on pre-existing soil conditions which make these impacts highly site-specific.

Soil property dynamics across invaded and un-invaded plots

In our study, we noted a significant influence on soil properties across various sites in the Kashmir Himalaya due to the invasion of *C. canadensis*. The soil properties exhibited notably higher levels in invaded plots compared to non-invaded ones. These outcomes substantiate our initial hypothesis and align well with prior research conducted worldwide on the impact of plant invasion on soil properties [48–52]. For instance, earlier studies have reported similar findings regarding *Lantana camara* invasion. Comparable results were observed in India's tropical dry deciduous forest [48]. Parallel outcomes were also reported in Brisbane, Australia [53], and in the Eastern Cape, South Africa [50]. Additionally, distinct shifts in soil properties were observed within central Himalayan Chir forests driven by the invasion of *L. camara* and *A. Adenophora* [51].

Additionally, our results indicated that invasion by this plant significantly altered OC, N, pH, EC, and various micronutrients in soil across study sites. For instance, the electrical conductivity dropped significantly in invaded plots relative to un-invaded plots. Similar findings observed a significant drop in soil EC invaded by *Carpobrotus edulis* as compared to the non-invasive reference zones [53]. Similarly, it was observed that *L. vulgare* invasion decreased soil electrical conductivity [32], but there are many other studies that show decreased electrical conductivity in the alien plant invaded soils [54,55]. Furthermore, the majority of the invaded soils exhibited alkaline profile (pH values > 7.5), which was significantly higher (p < 0.001) when compared with their un-invaded counterparts across all study sites. Studies have indicated that exotic invasive species have a tendency to elevate soil pH, creating conditions conducive to their own growth [11]. This finding aligns with research conducted on various other invasive plants like *Alliaria petiolate* [56], Acacia *sieberiana* [57], *Parthenium hysterophorus* [26,58], *L. vulgare* [32], *Lantana camara* and *Ageratum adenophora* [51]. The likely cause for this increase could be attributed to the rapid uptake of nitrate ions from the rhizospheric soil by invasive plant species, consequently elevating soil pH. Consequently, this relationship directly connects declining soil nitrates with elevated soil pH [59].

In this study, significant differences (p < 0.05) in soil macronutrients, OC, and N were observed between IN and UN plots across all sampling sites. This trend aligns with the previous research documenting the effects of other invasive plants on soil macronutrients [32,53,55,60]. The rise in OC and N levels in IN plots compared to UN plots might be attributed to the vigorous growth and taller structure of these invasive herbaceous plants, resulting in a greater above-ground biomass than co-occurring species. Comparable findings have been reported for other non-native plants such as *Solidago canadensis* [61], *L. vulgare* [62], *A. cotula* [55]. Additionally, studies by [13] indicate higher inorganic-N pools in areas invaded by *Hyptis suaveolens* compared to uninvaded areas. This increased nitrogen pool in the soil may drive microbial processes particularly bacterial growth,

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contributing to its success in invasion. Moreover, studies suggest that species like *A. adenophora* and *L. camara* generate higher litterfall and biomass, which subsequently enriches nutrient levels in invaded soils [51]. This pattern of increased nitrogen coupled lower phosphorus availability in invaded areas is well documented in previous studies as well [12,63]. Additionally, the unpalatability of some invasive species to domestic livestock results in higher aboveground biomass, further influencing nutrient concentrations in IN plots. The increased aboveground biomass and faster decomposition rate in IN plots could potentially explain the observed increase in OC and N concentrations [17,55,64,65]. Alternatively, the observed increase in pH might have driven the higher availability of OC and N because soil pH fundamentally regulates nutrient dynamics in the invaded soils [53,66,67]. Contrary to expectations, higher concentrations of phosphorus in soil were observed in UN plots than IN plots. This contrasts with some studies reporting an increase in soil P concentration due to plant invasions [26,50]. Nevertheless, our findings align with many studies that have documented that plant invasion led to a decline in soil P [12,61,68,69]. This decrease might be driven by increased arbuscular mycorrhizal (AM) fungi colonisation post-invasion [70], as higher hyphal density could decrease soil P concentrations [12,71]. Consequently, AM fungal colonization enhancing the efficiency of nutrient absorption by roots, allowing the plants to draw more P from the soil. Results have shown that soil micronutrients including copper (Cu), zinc (Zn) manganese (Mn), and iron (Fe), exhibited significantly increased concentrations in UN plots compared to IN plots across all sites ($p < 0.001$ and 0.01) (Table 2). Contrary to our findings, it has been observed that plant invasions actually led to an increase in micronutrient concentrations in the soil [15,55]. However, our results align with the studies which indicated a decrease in soil micronutrient concentrations subsequent to invasions by *Lantana camara* in Australia and *L. vulgare* in the Kashmir Himalaya [32,53]. The exact mechanism through which invasive plants modulate soil micronutrient dynamics remains relatively underexplored. However, a plausible explanation for this decrease is that these micronutrients occur only in trace amounts within the soil. Because invasive plants grow rapidly and dominate the plant community, they swiftly absorb and utilize these limited resources, ultimately depleting them in invaded areas [53].

Correlation and contribution of soil parameters

This study highlighted a correlation that was not significant in the invaded plot of *C. canadensis*. This finding aligns with several other studies [72–74]. This association is likely due to the intimate relationship between soil nitrogen dynamics and organic carbon, as most nitrogen exists within organic compounds. Consequently, the release of nitrogen from soil organic matter occurs proportionately [75–77]. The proliferation of invasive plants has been facilitated by their genetic and phenotypic adaptations, allowing them to adjust to changing climatic conditions worldwide in recent decades [78]. Within invaded habitats, these species drive modifications in soil physical and chemical parameters to shift nutrient dynamics. In our current study, we observed a correlation between soil pH, OC and N in invaded regions. When examining PCA biplots, it was evident that soil micronutrients and phosphorus tended to align more with the uninvaded conditions rather than the invaded ones. *C. canadensis* is recognized as dominant invader in disturbed or nutrient-rich soils, appear to assimilate more phosphorus to support their vigorous growth, ultimately leading to a reduction in soil phosphorus levels. The escalated levels of OC and N in invaded plots might be attributed to the substantial production of biomass and litter by this invasive species. Notably, invasive plants have been reported to accelerate litter decomposition, potentially contributing to increased OC and N content in invaded soils. Overall, our study underscores that *C. canadensis* significantly alter soil physicochemical properties, enriching the soil substrate with nitrogen, thereby potentially facilitating the invasion process. These findings offer insights that could aid in devising strategies to mitigate their impact and implement restoration efforts aimed at reinstating native vegetation. Management strategies such as mechanical uprooting or converting harvested biomass into value-added products like biochar may represent effective approaches for eradicating these invasive species from the Indian Himalayas.

Insights in invasion management

Recent habitat restoration efforts have relied primarily on manual removal or chemical herbicides to control invasive plant populations [79,80]. However, such efforts have often failed to fully remove the impact of invasive species even after their removal, as the persistent seed bank in the soil ensures their continued presence [81]. Moreover, the disturbance caused by invasive plant removal can lead to the invasion of other species, which is known as "invasional meltdown" [82,83]. Therefore, to effectively manage invasive plants, a holistic understanding of their ecological impact on soil properties and dynamics is essential [21,84]. Plant-soil feedbacks tend to be positive in invaded communities, while negative feedbacks are characteristic of native ones [85,86]. A major ecological concern is the phenomenon of invasional meltdown, wherein initial invasive species modify soil characters to benefit themselves and simultaneously facilitate the subsequent invasions [87–89]. Therefore, controlling invasive plants takes more than just pulling them out of the ground, but also an understanding of their subterranean feedback loops and their effects on soil properties and dynamics [86,90]. By considering these factors, restoration and management efforts may be optimized.

Conclusion

This research marks a crucial first step in bridging a major knowledge gap of how global plant invaders like *L. vulgare, A. cotula*, and *C. canadensis* disrupt and alter the on belowground soil ecosystems. These findings highlight that invasion by these plants causes a profound underground shift in the physicochemical properties of soil, including increased pH, total N, electrical conductivity, soil organic C and soil micronutrients. A significant enhancement in soil properties, especially its nutrient profiles, generates a positive feedback loop that facilitates the establishment of invasive plants. Furthermore, accelerated mineralization likely optimizes nutrient uptake by roots, fuelling rapid growth and colonization. Specifically, soil organic carbon and total nitrogen levels were markedly elevated in invaded zones relative to un-invaded control sites. The study suggests that plant invasion has significant impacts on soil properties, and the differences in soil properties could vary with plant species, site, and soil type. The findings could have important implications for soil management practices in invaded areas. Nevertheless, future research studies need to precisely examine how these alterations in the soil system dynamics influence plant growth and diversity. These novel insights will

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eventually pave the foundation for designing scientific invasion management protocol.

Author Contributions

Mohd Asgar Khan conceived the study. Mohd Asgar Khan, Javaid Ahmad and Aadil Farooq War conducted the experimental work and also performed the data analysis. Mohd Asgar Khan and Aadil Farooq War prepared the manuscript draft. Mohd Asgar Khan reviewed and revised the manuscript.

Availability of Data and Material

All data generated during this study have been included in this article

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Ethics Approval and Consent to Participate

Not applicable

Competing interest

Not applicable.

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