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ORIGINAL ARTICLE

Heavy Metal Contamination of Forest Soils by Vehicular Emissions: Ecological Risks and Effects on Tree Productivity

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Abstract

An ecological study was conducted to evaluate the levels and effects of heavy metals on forest surface soils along highways. We hypothesized that vehicles in highways emit considerable levels of metals, affecting plant diversity and productivity. Pearson correlation, cluster, and regression analysis were used to prove these relationships. Furthermore, ecological risk assessments were quantified using the geo-accumulation index, pollution index, pollution load index, and ecological risk index. Results indicated soil samples from Site II (roadway) had higher levels of metals than Site I (control), suggesting that highway traversing via forests emit considerable amounts of metals into the surface soil. The most intriguing aspect is that species such as *Bidens Pilosa* and *Arundo donax* were frequently recorded at Site II. The predominance of such species indicates contaminated sites favouring metal tolerance species. Ecological risk indices revealed that Cd, Mn, and Pb contributed to ecological risk; their pollution ranged from unpolluted to heavily polluted ecosystem. Correlation analysis found a pronounced negative link between metals and diversity; the correlation matrix was −83%, −94%, −65%, −75%, −47%, −57% and − 38% for grass diversity, and − 59%, −74%, −89%, −66%, −81%, −81% and − 83% for forb diversity with Cd, Cr, Ni, Pb, Zn, Cu and Mn, respectively. Furthermore, negative correlations for tree production of −80%, −79%, −76%, −71%, −67%, −53% and − 41% were recorded with Cd, Cr, Ni, Pb, Zn, Cu and Mn, respectively. Nevertheless, metals accounted for 74% variance in tree productivity. The strong negative link observed in this study demonstrates the effects of metals on diversity and productivity, which requires monitoring for preventing serious environmental consequences.

Highlights

- Excessive road traffic contributes to the release of heavy metal in forests.
- Heavy metals in surface soils threaten plant diversity and productivity.
- Cd, Mn and Pb are the most substantial contributors to ecological risks.

Keywords Biodiversity · Ecological risk · Environmental pollution · Heavy metals · Plant productivity

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1 Introduction

Heavy metal pollution by traffic-related emissions along roadway traversing through protected forests induces changes in plant species, affecting plant community structure, biodiversity, and ecosystem service (Galal et al. 2021; Yang et al. 2020). Deposition of metal such as nickel (Ni), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chromium (Cr), arsenic (As), mercury (Hg), lead (Pb), and cadmium (Cd) in the environment has become a serious global concern (Adimalla 2020; Bernardino et al. 2019; Dutta et al. 2021; Shi et al. 2019). Their contaminations disrupt the natural biogeochemical cycle (Kumar et al. 2019) due to their non-biodegradability, ecological risks, toxicity, bio-geochemical recycling, extended biological half-lives, and persistence (Carvalho et al. 2020; Kaur et al. 2020). They also interfere with ecosystem, health and nutrient turnover supply (Hiller et al. 2021; Huang et al. 2020). Thus, ecologists and environmentalists have a growing interest in understanding these relationships. Their interest is attributed to the world researchers' priority on the impacts of heavy metals on the environment (Kothandaraman et al. 2020; Kumar et al. 2020; Li et al. 2020).

India is the second most populated country globally and the most extensively contaminated with heavy metals due to anthropogenic activities ((Huang et al. 2020; Singh et al. 2020), which cause significant deposition of heavy metals in the environment (Khanam et al. 2020), including protected forests that are highly traversed by national highways. Apart from being one of the most polluted countries, India has a significant forest with diverse flora and is currently ranked 10th in global forest cover with about 69.1 million hectares of forests (Dibaba et al. 2019; Raha et al. 2020). Highways that pass through protected forest ecosystems have been identified as significant polluters, contributing to the accumulation of metals in surface soils (Devi et al. 2019; Kaur et al. 2020). The high level of heavy metal deposition in these areas is responsible for changes in the plant community, diversity, and productivity potentials (Danelli et al. 2021; Khalid et al. 2021; Sheng et al. 2021). Studies have reported that the concentration of heavy metals in roadside soils is explained by the presence of materials in cars associated with these metals (Christoforidis and Stamatis 2009). For instance, Pb origin is attributed to alkyl-lead compounds as anti-knock additives in petrol. Metals, such as Cu, Fe, Cr, Mn and Zn, are essential components of many alloys, pipes, wires and tires, as well as parts of automotive engines (Sert et al. 2019). These metals are released by automobile exhaust during car motor combustion, fluid leakage, burning of fuel, wearing out of tires, and corrosion of batteries and radiators (Aslam et al. 2013; Chen et al. 2021). The contamination caused by heavy metals along roadside soils can be re-suspended and distributed by scattering into the surrounding environment as a result of wind, intensity of precipitation, rainfall-runoff, and infiltration of contaminated water (Ghosh et al. 2020; Hiller et al. 2021; Jeong et al. 2020; Werkenthin et al. 2014). Heavy metals pollute the surrounding ecosystems and affect soil quality by changing physical properties (Meng et al. 2021). The interaction of physiological and biochemical activities of plant species includes photosynthesis (Danelli et al. 2021; Diarra and Prasad 2021; Kumar et al. 2021).

Studies have shown that excessive traffic enhances heavy metal deposition and exposure in roadways with deleterious effects on both animals and vegetation (Bhuiyan et al. 2021; Huang et al. 2020; Khalid et al. 2021; Zárate-Quiñones et al. 2021). For instance, Singh et al. (2018) reported the impact of heavy metal due to vehicular emissions on soil quality. Their study indicated a significant decrease in moisture content, organic carbon, available nitrogen, and potassium along roadsides. Similarly, Zanello et al. (2018) realized that emissions from road traffic in Brazil promoted the increase of heavy metals, especially Zn and Pb. These metals were found to concentrate in the roots of grass species (*Brachiaria*), affecting their growth. Bhuiyan et al. (2021) reported heavy metal contamination in Dhaka (Bangladesh) soil with serious concern for the ecological system. Sheng et al. (2021) evaluated the relationship between heavy metal pollution and biodiversity conservation of moss taxa in the *Nancha* manganese mining area in China. They have observed that the effect of metals on species diversity was significant. Li et al. (2020) reported negative impacts of heavy metals on bryophyte distribution and diversity in Haolong Sinkhole, China. They called upon an effective way to protect bryophytes from minimizing further damage.

On the other hand, studies appreciated the effects of heavy metals on plant biomass productivity potential. Ng et al. (2020) realized the remarkable ability of plant species to accumulate metals in soils. Grass species (*Vetiver*) exposed to contaminated soils accumulated more Zn (3322 mg kg^{-1}) followed by Cu (430 mg kg^{-1}), Pb (197 mg kg^{-1}), and Cd (100 mg kg^{-1}) with less biomass production. Similarly, Petukhov et al. (2020) observed that herb species like *Poa pratensis* and *Trifolium rubens* accumulated more heavy metals from urban (Russian Federation) contaminated soils than the control site. Moreover, Shawon et al. (2021) observed high concentrations of Zn, As, Cu, Ni, Pb, and Cr in rice grains in irrigation water from polluted rivers in Dhaka city of Bangladesh. An experiment conducted by Danelli et al. (2021) in the Caffaro area (Italy) used grass species (*Arundo donax* L.) as the phytoextraction of heavy metals. It was observed that *A. donax* removed about 3.87 kg ha^{-1} of Zn, 2.09 kg ha^{-1} of Cu, and 0.007 kg ha^{-1} of Cd from the contaminated soils. Galal et al. (2021) investigated the uptake capability of heavy metals and their impact on the growth dynamics of castor beans in Egypt. They realized that castor beans grown on contaminated soils recorded the lowest size index, volume, and the number of leaves. Khanam et al. (2020) reported that exposure of plants to metals results in a decrease in leaf growth and CO_2 assimilation. Heavy metals can cause chemical interactions that synergistically affect plant productivity (Singh et al. 2020), thereby posing their toxicity to humans via the food chain (Fajardo et al. 2020; Kumar et al. 2019).

Other global reported data on heavy metal concentrations along roadsides include those of: Alsbou and Al-Khashman (2018), in Petra region, Jordan; Achadu et al. (2015) in the city of Wukari, Northeast, Nigeria; Bernardino et al. (2019) in Rio de Janeiro, Brazil; Christoforidis and Stamatis (2009) in Kavala, Greece; Werkenthin et al. (2014) in major roads of cities in Europe; Ghosh et al. (2020) in Delhi and Kolkata, India; Hiller et al. (2021) in the town of Bratislava, Slovak Republic; Khan et al. (2011) along a national highway in Pakistan; Saeedi et al. (2009) along a highway in Iran; Singh et al. (2018) in Pahalgam roadside, India; Sutherland and Tolosa (2000) in Manoa Basin, USA; Zanello et al. (2018) in highways in Brazil; Devi et al. (2019) in the national highway crossing through the Kaziranga National Park in India.

Despite the significant relationship between metals, plant diversity and productivity, such data in protected forests of India is highly ignored in the literature. The available reported data in the country focused on describing the levels of heavy metals in other land uses like industrial areas, urban areas, mining places and water bodies/wetland ecosystems, as well as their effects on human health (Devi et al. 2019; Kaur et al. 2020; Kaushik et al. 2021; Kumar et al. 2019; Mishra and Kumar 2021; Rai et al. 2014; Sharma et al. 2018; Siddiqui et al. 2020). The baseline data that characterize the levels of the heavy metals in protected forests concerning plant diversity, their biomass production potential and ecological risks are still insipient and seldom reported. Even the scant available literature about the protected forests of India is mostly concerned with dust deposition and air pollution (Devi et al. 2019; Rai et al. 2014; Siddiqui et al. 2020; Singh et al. 2020); hence, insufficient data are provided on establishing proper mitigation against biodiversity loss. Thus, the need to quantify heavy metal concentrations in forest ecosystems traversed by national highways is seen as a necessary undertaking.

Consequently, to bridge the existing knowledge gap and promote effective forest management, a two-year detailed ecological investigation was conducted in two protected reserved forests (RFs) of Assam, a state in northeast India. The two RFs were chosen because they connect urban and rural areas with the busy motorized highway that traverses via them. The aims of the study were: (i) to quantify the concentration of heavy metals in surface soils along the roadway of these RFs; (ii) to evaluate the ecological risks; and (iii) to predict the impact of heavy metals on plant diversity and productivity potential. We divided the studied forests into two sampling sites: Site I (control, study comparative responses) and Site II (experimental/along roadway).

2 Materials and Methods

2.1 Description of the Study Area

The study was conducted in two RFs, namely Balipara RF and Bhomoraguri RF of Sonitpur district, Assam northeast India. These two RFs are 45.34 km apart from each other. The two RFs were chosen due to the national highway (NH-15), which crosses them. The NH-15 is one of the busiest motorized freight transit operating throughout the year. It is known for its high traffic density and regular movement of heavy-duty vehicles, which connects all major cities of the state. The precise locations of the two RFs are shown in Fig. 1. The district is one of the 33 administrative districts located in the north of the central Brahmaputra valley between 92° 16′E and 93° 43′E longitudes, and 26° 30’N to 27°N latitudes, with an average elevation of 70 to 75 m above mean sea level (Nath et al. 2013). RFs in the district cover an area of 935.38 km^2 (Baruah et al. 2007). The district’s northern and southern limits are bounded by the Himalayan foothills and the Brahmaputra River (Nath et al. 2013). It is located in a subtropical climatic zone with a monsoon climate with hot and humid summers with temperatures ranging from 7 to 36 °C on average (Saxena et al. 2014). The rainy season begins in early April, with an annual average of 1700 to 2200 mm, influencing the region’s climate (Baruah et al. 2007).

2.2 Soil Sampling

Soil samples were collected from two sampling sites (Site I and Site II) in both RFs from 2019 to 2020. Site I was considered a control site, while Site II was treated as an experimental site (along roadway). Samples in Site I were taken at about 200 m away from the highway towards the forest (Werkenthin et al. 2014; Singh et al. 2020). The 200 m distance was deemed sufficient to be free or minimally exposed to automobile emission and other related road traffic metal discharges (Trombulak and Frissell 2000). One hundred twenty (120) surface soil samples (i.e., 60 from each RF) at a depth of 0–15 cm, weighing 0.5 kg, were collected using a hand auger. Soil samples along the roadway (Site II) were gathered at a distance of 10 m away from the road’s edges, as per Hiller et al. (2021). Soil sampling was done seasonally, i.e., in the wet season (June to November) and the dry season (December to May). The soil samples were air-dried in a dust-free environment for two weeks at room temperature (25 °C), ground with a wooden pestle and mortar to break soil

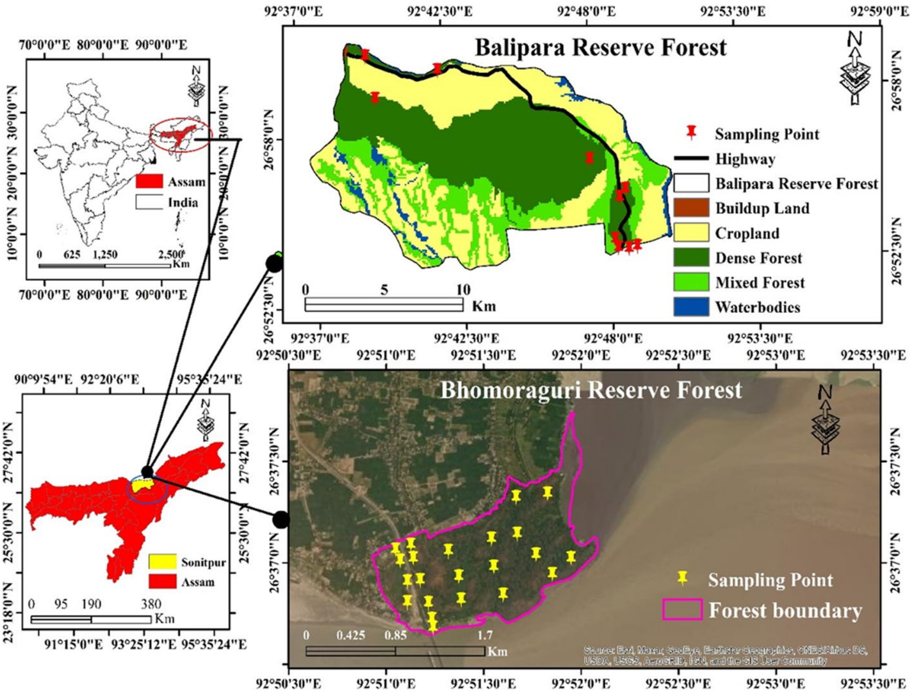

Fig. 1 The sketch map depicts Balipara and Bhomoraguri RFs of Assam, northeast India

lumps. The soil samples were sieved through a 2 mm and homogenized, securely packaged, and brought to Ecology and Biodiversity Research Laboratory at Tezpur University for pretreatment and further analysis.

2.3 Assessment of Plant Species Diversity

A total of 60 circular plots of 15 radii (30 Bhomoraguri RF and 30 Balipara RF) were systematically made along transects for vegetation sampling. Four quadrants of 0.5 m by 0.5 m were established to record herbaceous species within each plot. The frequency of individual herbs within quadrats was recorded (Czapiewska and Dyderski 2019). Community structures such as abundances, density, and basal areas were calculated according to Curtis and McIntosh (1950). The importance value index (IVI) was determined by the sum of relative frequencies, relative densities, and relative dominance (Misra 1989). Plant diversity measures such as the Shannon-Wiener diversity index (H′) and Simpson's dominance index (Cd) were calculated following methods established by Shannon and Weaver (1949) and Simpson (1949), respectively.

2.4 Estimation of Tree Biomass Productivity Potential

A non-destructive approach was used to estimate tree biomass productivity potentials. The allometric model developed by Nath et al. (2019) was used to quantify tree biomass production. The model was selected based on its specificity covering India's dry tropical,

tropical semi-evergreen, tropical wet evergreen, sub-tropical broad-leaved, and sub-tropical pine forests. This method requires quantitative data like tree heights, diameter at trunk height and wood density (Chave et al. 2014). Tree heights (m) and diameter at trunk height (cm) were collected from individual tree species using Suunto Clinometer (PM-5/360 PC) and measuring tape, respectively. The tree wood density for species-specific value was obtained from the global wood density database (Chave et al. 2009). A total of 12 dominant tree species characterized by uniform height and girth were selected from each RF. The distance of trees from the edge of the roadway did not exceed 10 m. Eqs. (1) to (4) were used to estimate tree biomass productivity potential.

$$AGB(kg/tree) = 0.32 \times \left(H\,\delta\,D^2\right)^{0.75} \times 1.34 \tag{1}$$

$$BGB(kg/tree) = AGB \times 0.26 \tag{2}$$

$$TB(kg/tree) = AGB + BGB \tag{3}$$

$$TC(kg/tree) = TB \times 0.47 \tag{4}$$

where H is tree height (m); δ is the wood density (kg/m^3); D is the diameter at trunk height (cm); AGB is the aboveground biomass (kg/tree); BGB is the belowground biomass (kg/tree); TB is the total biomass (kg/tree); and TC is the tree carbon stocking potential. (kg/tree).

2.5 Reagents

Throughout the laboratory analysis, analytical solvents and reagents were of GR grade with a high spectroscopic purity (99.9%), purchased from Merck Specialties Private Ltd., India, and were used without purification unless stated otherwise. All glass wears (made of Pyrex), plastic vessels, and containers were thoroughly cleaned, treated with 1% dilute nitric acid, and rinsed with double distilled water several times, followed by air-drying to avoid errors from impurities. All the required dilution for calibration standards and sample preparation were double-distilled (Dutta et al. 2021; Alsbou and Al-Khashman 2018).

2.6 Quality Assurance and Analytical Procedures

Appropriate quality assurance procedures were carried out to ensure the reliability and validity of the results. The present study employed an Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) in detecting the concentration of heavy metals. The ICP-MS is known to be a powerful technique for multi-elemental analysis. The instrument was optimized according to the procedure described in the operation manual. The detectors, gas flow, valves, quadrupole, inlet system, plasma power, and pressure levels were set at the desired levels (Khan et al. 2021). Filters and peristaltic pumps were cleaned with 1% dilute HNO_3 and properly positioned. Validation for the estimation of studied metals was done using certified standard reference material (No. HC073848, CertiPUR Reference Material, INORGANIC VENTURES, Technology VA 24073 USA). The accuracy of the analytical procedure for metals was confirmed using standard stock (IV-STOCK-4 M2-MEB656821, Merck CertiPUR®). Standard stock solution for metals was diluted to prepare five working standards and blank solutions. Standards were prepared by adding the appropriate quantity of a multi-elemental stock solution. Standards were prepared at different known concentrations (i.e., 18.75, 37.50, 75.00, 150.00 and 300.00 ppb). Each element had a calibration run before sample analysis until the recommended correlation values on calibration curves were obtained. The correlation values (R^2) for metals were 0.9998, 0.9896, 0.9984, 0.9568, 0.9988, 0.9997 and 0.9608 for Cd, Cr, Ni, Pb, Zn, Cu and Mn, respectively.

During analysis, the blanks were run intermittently to ensure that the analysis was of good quality, and washings were supplied at regular intervals (Sharma et al. 2018). The precision of results were evaluated through replicate analysis (Alsbou and Al-Khashman 2018). Each sample was examined three times, and the average values were reported. The instrument detection limit was calculated using the raw intensity data from the standard and the blank using the equation given in the operating manual and detailed by Tomoko in his technical report of 2017 (Tomoko 2017) and Shrivastava and Gupta (2011). The detection limit was found to be less than 0.001 part per billion (ppb). The quantification limit was determined using standard deviations (SDs) as per Shrivastava and Gupta (2011). Briefly, 5 mL of each sample was diluted 100 times, analyzed seven times, followed by computing standard deviations (SDs). The quantification limit for each metal were: 0.000941, 0.000048, 0.00059, 0.00183, 0.0000671, 0.000692, and 0.000874 for Cd, Cr, Ni, Pb, Zn, Cu, and Mn, respectively. They ranged between 1.25% and 3.16%, which was considered satisfactory for environmental analysis and agreed with the certified values (± 5%).

2.7 Elemental Analysis

The physiochemical properties of the soil samples were analyzed as per standard methods. Soil pH and electrical conductivity (EC) were determined in 1:2 soil water suspensions using a digital pH meter and EC meter, respectively. The Walkley-Black wet digestion method determined soil organic carbon (SOC) (Adhikari and Bhattacharyya 2015). The available N, P, and K were determined by potassium permanganate, Olsen, and neutral normal ammonium acetate methods (Singh et al. 2018). The contents of heavy metals (Cd, Cr, Ni, Pb, Cu, Zn, and Mn) in soil were extracted using chelating agents (EDTA and DTPA) (García and Millán 1994; Pagotto et al. 2010). Metals (Cd, Ni Cu, Zn, and Mn) were extracted with 5 mM diethylenetriaminepentaacetic acid (DTPA)/10 mM $CaCl_2$/100 M triethanolamine (TEA) at pH 7.3. In comparison, Cr and Pb were extracted with 0.05 M Ethylenediaminetetraacetic acid (EDTA) and ammonium nitrate extraction method at pH 7.0. The obtained filtrates were double filtered through Whatman filter paper No.1, followed by Whatman Syringe filter (size 0.45 µm; Whatman, UK). The concentrations of heavy metals in an aliquot of the filtrates were measured using Inductively Coupled Plasma-Mass Spectrometry (iCAP RQ ICP-MS; Thermo Fisher Scientific, India).

2.8 Ecological Risks Assessments

Numerous ecological indices such as the geo-accumulation index (Igeo), pollution index (PI), pollution load index (PLI), and ecological risk index (RI) were used to assess ecological risks (Dutta et al. 2021). The choice of these indices was based on the need of the study; for instance, the geo-accumulation index was used to determine the contamination of individual heavy metals in the soil compared to pre-industrial levels (Shi et al. 2019). The pollution index aims to measure pollution levels on a particular land-use pattern as the results of anthropogenic concerning global or local background value (Adhikari and Bhattacharyya 2015). On the other hand, the pollution load index was employed to measure heavy metal pollution at each sampling site (Hu et al. 2013). Furthermore, the ecological risk index was used to assess the overall possible ecological risk by considering the specific toxic response of each metal (Dutta et al. 2021). Appropriate categories with varying classification scales of pollution and contamination were used as quantifiable characteristics to provide a realistic estimate of pollution and contamination levels (Dutta et al. 2021; Kaushik et al. 2021). The typical standard region-specific geochemical baseline (background concentration value of natural soils) was unavailable, particularly for the studied region. Therefore,

the background levels were determined by the levels in the parent material in the soil profile due to pedogenesis, reported by other scholars, as shown in Table 1 (Adimalla 2020; Kaur et al. 2020; Kumar et al. 2019).

2.8.1 Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) is a quantitative approach for determining heavy metal contamination in soil. It assesses the extent of metal pollution in soils and allows us to compare current and pre-industrial levels (Shi et al. 2019). The index can also identify lithogenic impacts as a source of metal pollution. Eq. (5) was used to calculate the geo-accumulation index:.

$$I_{geo} = \log_2\left[\frac{C_n}{1.5 \times B_n}\right] \quad (5)$$

where C_n denotes the measured metal pollutant concentration in soil (mg kg^{-1}) and B_n denotes the metal concentration (mg kg^{-1}) in the geochemical background (i.e., unpolluted sample or in natural forest). The levels of metal contamination are classified as: (i) practically uncontaminated (for Igeo $\leq$0); (ii) uncontaminated to moderately contaminated (for 0 < Igeo <1); (iii) moderately contaminated (for 1 < Igeo <2); (iv) moderately to heavily contaminated (for 2 < Igeo <3); (v) heavily contaminated (for 3 < Igeo <4); (vi) heavily to extremely contaminated (for 4 < Igeo <5) and (vii) extremely contaminated (for 5 < Igeo > 6) (Adimalla 2020).

2.8.2 Pollution Index (PI)

The pollution index (PI) is the ratio of the heavy metal content in the soil sample tested to the metal natural background concentration (Dutta et al. 2021). It is commonly expressed as the percentage of the metal content of the sample that exceeds the reference material. The index measures metal pollution by considering land-use patterns and anthropogenic soil impacts, aiming to match average metal concentrations in a given soil to a global or local natural background value (Adhikari and Bhattacharyya 2015; Hu et al. 2013). Eq. (6) was used to determine the pollution index (PI):

$$PI = \frac{C_n}{B_n} \quad (6)$$

where C_n is the element's measured concentration in soil (mg kg^{-1}) and B_n is the local natural background value (mg kg^{-1}). Each metal pollutant was categorized as: (i) low (for PI $\leq$1.0); (ii) medium (for 1.0 < PI $\leq$3.0); and (iii) high (for PI >3.0) (Dutta et al. 2021).

Table 1 Geochemical background, toxic response factors, and permissible limits for Indian natural soils

Reference	Elements							Source
	Cd	Cr	Ni	Pb	Zn	Cu	Mn	
Geochemical background	1	90	27.7	13.1	22.1	56.5	209	Adimalla 2020; Kumar et al. 2019
Toxic response factors	30	2	5	5	1	5	1	Hakanson 1980; Shi et al. 2019
Permissible limits	3–6	200	75–150	250–500	300–600	135–270	4000	Kumar et al. 2019; Dutta et al. (2021)

2.8.3 Pollution Load Index (PLI)

The pollution load index (PLI) measures metal pollution at each sampling site (Hu et al. 2013). The PLI is calculated using contamination factors (C_r), the nth root of the factors multiplied together for each metal at each site (Shi et al. 2019). Its quotient is calculated by dividing each metal's concentration by the background values (Hu et al. 2013; Shi et al. 2019) (Eq. 7).

$$PLI = \sqrt[n]{C_r n_1 \times C_r n_2 \times C_r n_3 \times C_r n_4 \cdots \times C_r n_n} \tag{7}$$

where C_r is the contamination factor of an individual pollutant, and n is the number of metal pollutants that have been analyzed (Kaur et al. (2020). The value of PLI was divided into three categories: (i) no pollution (for $PLI < 1$); (ii) pollution levels are under control (for PLI =1) and (iii) soil considered polluted (for $PLI > 1$) (Kaur et al. 2020; Kaushik et al. 2021).

2.8.4 Ecological Risk Index (RI)

The ecological risk index (RI), which comprises the aggregate of risk indicators, was used to assess the overall possible ecological risk (Hu et al. 2013). It sets the ecosystem's total ecological risks by considering their particular toxic response elements (Dutta et al. 2021; Hakanson 1980). Thus, the potential ecological risk index (RI) was calculated as the sum of individual metal risk factors (E_i): Eqs. 8 and 9 were used to compute RI.

$$RI = \sum \left(E_i\right) \tag{8}$$

$$E_i = T_i \times f_i = T_i \left[\frac{C_i}{B_i}\right] \tag{9}$$

where E_i denotes the risk factor, T_i denotes the toxic-response factor for a specific metal, and f_i denotes the pollution index. RI values were categorized into four classes: (i) low ecological risk (for $RI < 180$); (ii) moderate ecological risk (for $150 \leq RI < 300$); (iii) considerable ecological risk (for $300 \leq RI < 600$); and (iv) very high ecological risk (for $RI \geq 600$). The E_i potential ecological risk was divided into five categories: (i) low potential ecological risk (for $E < 40$); (ii) moderate potential ecological risk (for $40 \leq E < 80$); (iii) considerable potential ecological risk (for $80 \leq E < 160$); (iv) high potential ecological risk (for $160 \leq E < 320$); and (v) very high potential ecological risk (for $E \geq 320$) (Hakanson 1980).

2.9 Effect of Heavy Metals on Plant Diversity and Tree Biomass Productivity Potential

The impacts of metals were predicted using different methods in an integrated and holistic approach because it is difficult to conclude the effects using a single method (Bhuiyan et al. 2021). Thus, the collective application of the Pearson correlation, Hierarchal cluster analysis, and Regression analysis was used to predict the impacts of metals. The Cluster analysis was used to detect groups and characterize the diverse interrelationships of metals based on their commonalities using the Ward methods.

2.10 Statistical Analysis

Descriptive statistics were used to represent the levels of different soil parameters and concentrations of heavy metal. The Shapiro-Wilk and Levene tests were employed to confirm normality and homogeneity of data, respectively. Significant variations in heavy metal concentrations between the two investigated Sites (Site I and Site II) were determined using an independent t-test with a significance level of $\alpha = 0.05$. A one-way ANOVA using the Fisher's Least Significant Difference Test (LSD) was also performed to determine whether the differences between mean for plant diversity were statistically significant at $p = 0.05$. Pearson's correlation and hierarchical cluster analysis were used to uncover correlations and patterns of similarity between heavy metals, plant diversity, and biomass productivity. A dendrogram was created using the Ward method and Euclidean distance. Stepwise regression analysis was employed to predict the impacts of heavy metals on tree biomass productivity potential. All statistical analyses were done using the SPSS Software ver. 20.0 (SPSS, Chicago, IL).

3 Results and Discussion

3.1 Soil Physicochemical Properties

Table 2 contains seasonal descriptive results for the evaluated soil physicochemical properties and heavy metal concentration parameters in Bhomoraguri and Baliapara RFs. The mean values for soil physicochemical properties along the roadway (Site II) of Bhomoraguri RF were 7.31 and 6.36 for pH, and 0.52 and 0.59 and 1.3 and 1.13 µS/cm for EC during dry and wet season, respectively. The available soil nutrients recorded along the roadway in Bhomoraguri RF were 19.49 and 18.9 mg kg^{-1} for N, 3.65 and 3.76 mg kg^{-1} for P, and 12.9 and 12.16 mg kg^{-1} for K for the dry and wet season, respectively. On the other hand, Balipara RF recorded 26.93 and 26.12 mg kg^{-1} for N, 18.19 and 318.76 mg kg^{-1} for P, and 6.61 and 6.23 mg kg^{-1} for K for the dry and wet season, respectively (Table 2). The present study observed a significant season fluctuation for the soil physicochemical parameters in both studied RFs ($p < 0.001$). The mean values of pH, SOC, available N, and K were higher in the dry season than in the wet season, while EC and the available P recorded higher values in the wet season than in the dry season. Comparing the two sampling sites (Site I and Site II) using the independent t-test, results revealed that differences between the two sites were statistically significant at $t = -0.57$, $df = 85.29$, $p < 0.000$; and $t = 40.39$, $df = 94.68$, $p < 0.000$, for Bhomoraguri RF and Balipara RF, respectively. The pH was slightly acidic in Site I while neutral to basic in Site II. The mean values of pH, EC, and P were observed higher in Site II; meanwhile, the SOC, N, and K values recorded greater values in Site I than in Site II for both studied RFs. The pH values in soil samples collected from Site II (roadway) were found with a greater mean value of 7.31 and 6.27 compared to Site I (6.14 and 5.27) for Bhomoraguri RF and Balipara RF, respectively. Similarly, EC (µS/cm) was more elevated in Site II, reaching about 0.59 and 0.15 µS/cm, compared to values of 0.28 and 0.07 in Site I for Bhomoraguri RF and Balipara RF, respectively. The

Table 2 Descriptive statistics for physicochemical properties and concentrations of heavy metals in the soils of the studied reseve forests

Parameters		Bhomoraguri RF				Balipara RF			
		Site I (control)		Site II (roadway)		Site I (control)		Site II (roadway)	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
pH	Range	5.98–6.5	5.32–5.79	7.12–7.74	6.19–6.73	4.46–5.63	3.97–5.01	5.31–6.7	4.62–5.83
	Mean ± SD	6.14 ± 0.159	5.47 ± 0.14	7.31 ± 0.19	6.36 ± 0.16	5.27 ± 0.30	4.69 ± 0.27	6.27 ± 0.36	5.46 ± 0.31
EC (μS/cm)	Range	0.18–0.44	0.20–0.48	0.36–0.89	0.41–1.00	0.03–0.11	0.04–0.12	0.07–0.22	0.08–0.25
	Mean ± SD	0.26 ± 0.11	0.28 ± 0.11	0.52 ± 0.21	0.59 ± 0.24	0.07 ± 0.02	0.07 ± 0.03	0.13 ± 0.05	0.15 ± 0.06
SOC (%)	Range	1.3–2.17	1.14–1.90	1.01–1.69	0.88–1.47	1.65–3.86	1.45–3.39	1.28–3.01	1.11–2.61
	Mean ± SD	1.67 ± 0.35	1.47 ± 0.31	1.30 ± 0.28	1.13 ± 0.24	2.22 ± 0.42	1.96 ± 0.37	1.73 ± 0.33	1.50 ± 0.28
N (mg kg^{-1})	Range	29.4–35.7	26.75–32.49	17.55–21.31	17.03–20.67	29.4–73.6	26.75–66.98	17.55–43.94	17.02–42.62
	Mean ± SD	32.64 ± 2.13	29.70 ± 1.95	19.49 ± 1.28	18.90 ± 1.24	45.11 ± 12.26	41.05 ± 11.15	26.93 ± 7.32	26.12 ± 7.09
P (mg kg^{-1})	Range	0.77–3.87	0.82–4.14	0.96–4.80	0.99–4.95	3.07–39.26	3.28–42.01	3.80–48.69	3.92–50.19
	Mean ± SD	2.94 ± 0.98	3.15 ± 1.05	3.65 ± 1.22	3.76 ± 1.25	14.67 ± 8.74	15.70 ± 9.36	18.19 ± 10.84	18.76 ± 11.18
K (mg kg^{-1})	Range	1.44–63.85	1.28–56.83	0.68–30.01	0.64–28.30	4.60–42.42	4.09–37.76	2.16–19.94	2.04–18.80
	Mean ± SD	27.45 ± 19.08	24.43 ± 16.98	12.90 ± 8.97	12.16 ± 8.46	14.06 ± 7.22	12.52 ± 6.43	6.61 ± 3.39	6.23 ± 11.18
Cd (mg kg^{-1})	Range	0.12–0.45	0.16–0.57	1.91–6.89	1.50–5.41	0.004–0.14	0.005–0.18	0.06–2.19	0.05–1.72
	Mean ± SD	0.19 ± 0.11	0.25 ± 0.14	2.96 ± 1.66	2.33 ± 1.30	0.03 ± 0.03	0.04 ± 0.04	0.53 ± 0.54	0.42 ± 0.42
Cr (mg kg^{-1})	Range	0.29–0.56	0.37–0.71	4.86–9.50	3.40–6.65	0.24–7.26	0.29–9.19	3.96–122.32	2.78–85.64
	Mean ± SD	0.38 ± 0.09	0.48 ± 0.12	6.37 ± 1.59	4.46 ± 1.12	0.97 ± 1.71	1.23 ± 2.16	16.32 ± 28.87	11.43 ± 20.21
Ni (mg kg^{-1})	Range	2.84–5.67	2.68–5.36	48.88–97.76	30.20–60.41	0.36–2.95	0.34–2.79	5.49–44.97	3.39–27.78
	Mean ± SD	4.39 ± 0.09	4.15 ± 0.89	75.67 ± 16.27	46.76 ± 1.12	1.20 ± 0.76	1.14 ± 0.72	18.29 ± 11.62	11.30 ± 7.18
Pb (mg kg^{-1})	Range	8.36–14.96	9.77–17.49	110.79–198.27	72.13–129.08	3.14–13.45	3.68–15.73	31.21–133.39	20.32–86.84
	Mean ± SD	10.19 ± 2.01	11.92 ± 2.35	135.07 ± 26.59	87.93 ± 17.31	5.99 ± 3.13	7.01 ± 3.66	59.46 ± 31.05	38.71 ± 20.21
Zn (mg kg^{-1})	Range	0.25–1.77	0.21–1.54	7.1–51.18	6.96–50.21	0.32–1.13	0.28–0.986	9.38–36.01	9.20–35.33
	Mean ± SD	0.85 ± 0.53	0.74 ± 0.46	24.56 ± 15.29	24.09 ± 15.00	0.56 ± 0.31	0.49 ± 0.27	17.49 ± 10.17	17.16 ± 9.98

Table 2 (continued)

Parameters		Bhomoraguri RF				Balipara RF			
Cu (mg kg^{-1})	Range	1.48–2.62	1.32–2.32	51.75–82.25	50.70–80.59	0.19–4.21	0.17–3.74	5.93–133.58	5.81–130.88
	Mean ± SD	1.88 ± 0.37	1.67 ± 0.33	64.81 ± 11.21	63.49 ± 10.98	1.26 ± 1.50	1.12 ± 1.33	40.13 ± 47.73	39.32 ± 46.76
Mn (mg kg^{-1})	Range	12.61–75.01	11.25–66.90	358.06–2129.61	307.46–1828.70	1.94–2.52	1.73–2.24	55.11–71.51	47.32–61.41
	Mean ± SD	40.69 ± 21.84	36.29 ± 19.47	1155.36 ± 619.87	992.12 ± 532.28	2.26 ± 0.21	2.02 ± 0.18	64.17 ± 5.96	55.11 ± 5.12

SOC (%) in Site I was significantly higher (1.67 and 2.22) than in Site II (1.13 and 1.73) for Bhomoraguri RF, and Balipara RF, respectively.

The differences in soil pH between the two sampling sites (Site I and Site II) for the studied RFs could be attributable to differences in exchangeable bases and heavy metal concentration between sites. The substantial leaching of interchangeable bases for the studied RFs is due to heavy rainfall conditions, which may have influenced the acidic character of the soil examined. According to Dutta et al. (2021), the higher leaching and rainy circumstances improve the exchange of bases and may promote the release of protons due to biochemical weathering. The relatively high pH in the samples collected in Site II, on the other hand, could be attributed to discharged metals from vehicular emissions that have modified the physicochemical properties of surface soils by de-acidifying and oxidizing them. Acidic soils enhance heavy metal mobility and adsorption on soil particles, while alkaline soils reduce mobility throughout the soil matrix (Adhikari and Bhattacharyya 2015).

Soil organic carbon (SOC) for samples collected from Site II was relatively lower than in Site I (Table 2), indicating a high SOC for the control site. The presence of stable litterfall and decomposition, which were then released from the vegetation in Site I (forest), could explain the relatively high level of SOC reported in this study. The amount of SOC depends on various parameters (soil texture, climate, vegetation, and land use pattern), which plays an important role in improving soil fertility and plant productivity. On the other hand, metal contaminants discharged along a roadway may have influenced such minor variance in these study sites. These metals may impact litter decomposition and nitrogen exchange as well as general soil health. Electrical conductivity (EC) was higher in Site II than Site I for both studied RFs. The observed discrepancies in the studied forests sites (Site I and II) could be attributed to the discharge and leaching of numerous soluble salt related compounds found in chemicals used in tarmac synthesis for road maintenance and construction. The salt-related slugs, resulting from the chemical used in the shattered stone, blended tar to produce tarmac, play a significant role in adding saline contents to the soil surface. The available N, P, and K concentrations vary significantly between the two sites. The levels of N and K were higher in samples collected from Site I than in samples collected from Site II for Bhomoraguri and Balipara RF.

Contrary to popular belief, the available P was higher in Site II (3.65 and 18.76 mg kg^{-1}) than in Site I (2.94 and 14.68 mg kg^{-1}) for Bhomoraguri and Balipara RF, respectively. The reason for decreased available P in the control site (Site I) might be attributed to the high uptake and fixation of P-related compounds by the dominant tree species (*Tectona grandis*). Furthermore, giant trees and regenerating plants quickly utilize phosphorus, iron, and aluminium (Shrestha and Kafle 2020), which could have reduced the amount of available P. Moreover, high P availability in soil samples collected from the roadway (Site II) could be attributed to vehicular discharge of P-related compounds. The pH of forest sections varied between 4.67 and 6.5, affecting P availability due to increased fixation by regenerating plants.

3.2 Concentration of Heavy Metals in Surface Soils

The present investigation found a significant difference in levels of heavy metals between seasons and sampling sites (Site I and Site II). The recorded concentration of the studied heavy metals along roadway of Bhomoraguri RF were 2.96 and 2.33 mg kg^{-1} for Cd, 6.37 and 4.46 mg kg^{-1} for Cr, 75.67 and 46.76 mg kg^{-1} for Ni, 135 and 87.93 mg kg^{-1}

for Pb, 24.56 and 24.09 mg kg^{-1} for Zn, 64.81 and 63.49 mg kg^{-1} for Cu, and 1155 and 992.12 mg kg^{-1} for Mn, for dry and wet season, respectively. Heavy metals such as Cr, Ni, Pb, and Mn varied significantly ($p < 0.05$) with seasons, while Cd, Zn, and Cu did not show any significantly different ($p > 0.05$) among seasons (dry and wet). However, the overall concentration of heavy metals was relatively high during the dry season compared to the wet season. For instance, the concentration of Ni was 75.67 and 46.76 mg kg^{-1} for the dry and wet season, respectively, Pb was 135 and 87.93 mg kg^{-1} for dry and wet season, respectively, and Mn was 1155.36 and 992.12 mg kg^{-1} for dry and wet, respectively in Bhomoraguri RF.

Based on sampling sites, heavy metal concentrations were found to be greater in Site II (roadway) than in Site I (control) (Table 2). Mn has the highest concentrations of 1155.36 and 64.17 mg kg^{-1} in Site II, followed by Pb (135.07 and 59.46 mg kg^{-1}). The lowest value was recorded by Cd (2.96 and 0.53 mg kg^{-1}) for Bhomoraguri RF and Balipara RF, respectively. The mean concentration was higher in Bhomoraguri RF than in Balipara RF. Human activities such as the ongoing large-scale bridge construction project along the Brahmaputra River, which runs through the forests, could have been influenced. Road diversions in the area have a serious concern for tree felling to accommodate the number of vehicles passing through the RFs. The creation of these temporary road diversions results in a significant shift in road geometry and vehicle speed. Devi et al. (2019) reported that road geometry directly impacts vehicle deceleration and acceleration, hence controlling metal pollutant load discharge and emissions from vehicular engines, as well as wear and tear. Cd recorded the lowest concentration values in both of the studied RFs. The sequence of heavy metal concentrations in Bhomoraguri RF was in the order of Mn > Pb > Ni > Cu > Zn > Cr > Cd. While in Balipara RF was in order of Mn > Pb > Cu > Ni > Zn > Cr > Cd.

Despite considerable differences in concentration levels among the examined heavy metal, the mean concentrations were below the Indian standards guideline for natural and roadside (Kaur et al. 2020). Most of the analyzed metals were even lower than the safe level of other international guidelines (Adimalla 2020; Kaur et al. 2020). For instance, the maximum mean concentration for Cd along the roadway in Bhomoraguri and Balipara RF was 2.97 and 0.53 mg kg^{-1}, respectively. At the same time, the permissible limits in soil for natural and roadside soils vary from 3 to 6 mg kg^{-1} (Kaur et al. 2020). The higher concentrations of metal pollutants in soil samples collected along the roadway (Site II) compared to control sites (Site I) suggest that the source of these metals could be automobile and vehicular emissions caused by road repair and fast-moving traffic. Jeong et al. (2020) reported that the common heavy metals released from vehicles on the road are Cd, Cu, Pb, and Zn, as they originate from wearing of vehicle parts. Although the concentration of Cd was lower than other metals, it has a high toxicity profile (Shi et al. 2019); therefore, it is essential to examine and understand its pathways. The concentrations of metal contaminants found in the present study accord with the findings of roadside soil and road dust in urban parks of Delhi, India (Siddiqui et al. 2020). It was difficult to establish accurate comparisons from the present study findings due to a lack of similar studies in the region. However, some metal pollution concentration studies from other places of the globe are presented for compararion and justification (Table 3).

The present study finding agrees with other reported data of India and the world at large. Werkenthin et al. (2014) realized that roadside surfaces cause an increase of soil pH even higher than 7 due to technogenic materials released by cars and alkaline deposition. Alsbou and Al-Khashman (2018) recorded low levels of Cd compared to other metals; however, the study realized that heavy metals originating from motor vehicles are deposited onto roadsides at a distance depending on the size of particles. The concentration

Table 3 Comparison for heavy metal status along roadways reported elsewhere in the world

Location	Heavy metals (mg kg^{-1})							References
	Cd	**Cr**	**Ni**	**Pb**	**Mn**	**Cu**	**Zn**	
Roadway along Bhomoraguri RF, India	2.64	5.41	61.21	111.50	1073.74	64.15	24.33	Present study
Roadway along Balipara RF, India	0.47	13.88	14.80	49.09	59.64	39.72	17.33	Present study
Bratislava, Slovak Republic	–	36.01	20.9	54.2	419	67.1	174	Hiller et al. (2021)
Dehli-Kolkata (NH-2), India	0.34–0.63	9.6–26.9	20.2–26.7	12.11–30.55	15.01–23.01	–	55.27–108.5	Ghosh et al. (2020)
Rio de Janeiro, Brazil	0.1–1	10.04–15.45	20.45	–	834.44	13.54	112.2	Bernardino et al. (2019)
City Highways, Brazil	–	81.9	–	39.7	–	379.3	–	Zanello et al. (2018)
Pahalgam, India	0.079		0.649	1.168	–	0.415	0.896	Singh et al. (2018)
Petra region, Jordan	1	–	–	177	–	19.1	129	Alsbou and Al-Khashman (2018)
Wukari NE, Nigeria	0.15–5.3	–	–	89.6–247.1	–	7.1–61.2	26.5–163.7	Achadu et al. (2015)
Major roads, European cities	0.1–10.7	0.4–290.3	2.7–314	5.1–1453	–	7–413	25–2618	Werkenthin et al. (2014)
United Arab Emirates Dubai	0.17–1.01	–	13.31–98.13	259.66–2784.45	57.95–166.43	15.51–65.90	91.34–166.43	Aslam et al. (2013)
National Highway (N-5), Pakistan	0.84	–	8.82	36.46	174	12.9	56.72	Khan et al. (2011)
Istanbul, Turkey	–	–	–	191	–	68.7	255	Guney et al. (2010)
Highways, Iran	3.9	47.98	90.32	699.3	–	–	614.31	Saeedi et al. (2009)
Kavalas region, Greece	0.2	193.2	58.2	359.4	–	42.7	137.8	Christoforidis and Stamatis (2009)
Manoa basin, USA	–	0.09	–	114	0.23	117	392	Sutherland and Tolosa (2000)

of these metals can be redistributed significantly and may have a great threat to the ecosystem. Wind direction and runoff water were among the factors for the re-distribution of metals. Similarly, Ghosh et al. (2020) observed the effects of seasonality on heavy metal concentration along the roadway, and they observed significant contamination of Cd which was maximum during pre-monsoon season.

The notable differences in levels of heavy metals in the present study compared to other studies could be site-specific. The disparities in metal pollutant concentrations observed across all comparisons could be attributable to the different sources of metal pollutants. These investigations were conducted in places impacted by industrial pollution, urbanization, or substantial agriculture. Thus, the elevated concentration could be attributable to the outflow of industrial wastewater, home sewage, and fertilizer applications. However, as previously stated, the practical reason for substantial augmentation is difficult to be identified from the present investigation because the current study dealt with soil samples polluted mainly by a single source of anthropogenic activity (i.e., vehicular emissions). According to Shi et al. (2019), the concentration of metal pollutants is influenced by the dominant anthropogenic activity in a given location. The use of Cd-containing phosphate fertilizer in nearby agricultural areas could result in high levels in the soil. The high concentrations of Pb containing chemicals in a specific ecosystem have resulted from industrialization and motor vehicle emissions into the atmosphere.

Several relevant pieces of literature reveal considerable concentrations of metals along the roadside (Table 3). Thus, the greater concentrations of metals along the roadway (Site II) in the present study support the hypothesis that these metals result from automotive emissions. This concentration could reach uncontrollable levels, causing environmental damage to nearby species unless monitored and controlled. For instance, an excess Nickel (Ni) in soils causes a variety of physiological and macroscopic responses, including chlorosis and necrosis, which impede plant development and root growth and inhibit the growth of primary roots (Adimalla 2020). Furthermore, metals such as lead, cadmium, and hexavalent chromium rank high based on prevalence, toxicity, and possible harm (Jha et al. 2016). These metals are among the top twenty on the list, and their persistence in the environment makes them potentially dangerous. As a result, their accumulation in surface soils and subsequent transmission from ground to plants is a major worry.

3.3 Ecological Risk Assessments

The results for ecological risk assessments using ecological indices are shown in Fig. 2. The geo-accumulation index (Igeo) in both studied RFs exhibited varying classes of contamination levels. The mean value of Igeo in Bhomoraguri RF for Cd, Cr, Ni, Pb, Zn, Cu, and Mn in Site II were 0.65, −4.7, 0.48, 2.45, −0.78, −0.42, and 1.54. These values were relatively higher as compared to those recorded in Site I (−2.94, −8.35, −3.32, −0.86, −5.71, −5.61 and −3.26). A similar trend was observed in Balipara RF (Fig. 2A). The findings showed that all soil samples collected from Site II (experimental) had a relatively higher contamination level than those in Site I. The soil samples from Site I (control) portrayed a practical uncontaminated category (Igeo ≤ 0) for both Bhomoraguri and Balipara RF, indicating that all heavy metals in Site I had no ecological harm. Igeo along roadway/experimental (Site II) ranged from moderately contaminated to heavily contaminated. Metals such as Cd, Ni, and Mn portrayed a moderately contaminated category, while Pb indicated heavily contaminated area in Bhomoraguri RF.

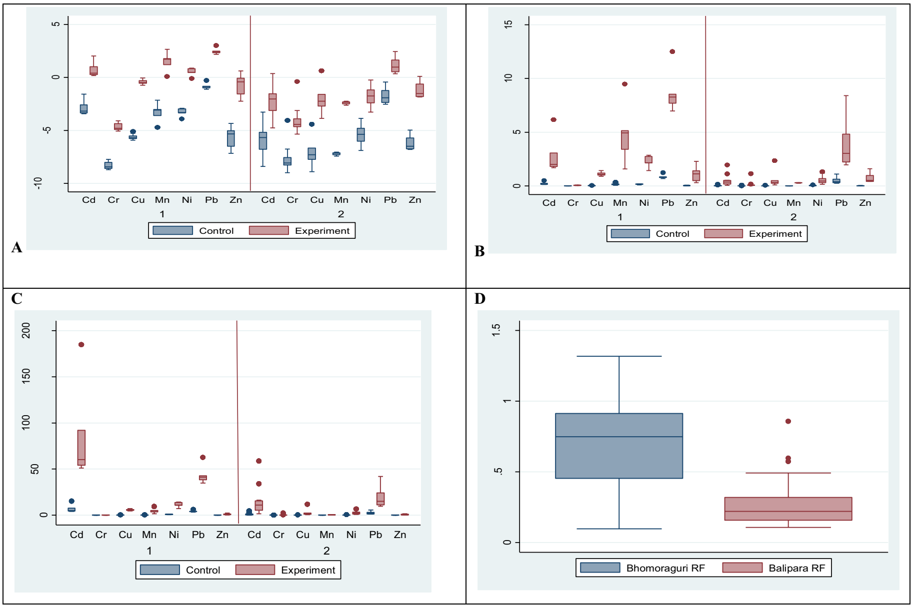

Fig. 2 Ecological risk indices showing levels of risk for Bhomoraguri RF (1) and Balipara RF (2) for both Site II (Experiment) and Site I (Control): **A**. geo-accumulation index (Igeo); **B**. pollution index (PI); **C**. pollution load index (PLI); and **D**. ecological risk index (RI)

Similarly, in Balipara RF, Pb was found to have the highest environmental harm than other studied metals concerning the geo-accumulation index. Thus, the highest amounts of contamination in surface soils along the roadway (Site II) were contributed by Pb, whereas Cr contributed the lowest level. Pb significantly affects ecological and environmental risk and plant diversity and production. Using pollution index (PI), an evaluation of ecological risks showed a varying pollution level ranging from low to high pollution (Fig. 2B). Metals such as Pb and Mn indicated high pollution levels (PI >3.0) in Bhomoraguri RF with the mean values of 8.5 and 5.12, respectively. Cd, Ni, Zn, and Cu, showed a medium category (1.0 < PI ≤3.0) of pollution, while Cr portrayed a low pollution category. Furthermore, except for Pb, which was categorized as a high polluting element (1.0 < PI ≤3.0), all other studied metals were classified as low polluting in Balipara RF. The domination of Pb in soil samples from Site II indicated that the surface soils along roadway travelling through RFs were moderate to heavily contaminated, with Pb, Mn, and Ni being the primary polluters. This shows that the most prevalent contaminants in surface soils along the roadway (Site II) were Pb, Mn, and Ni for all RFs studied. The great concentrations of these metals could be linked to automotive emissions and automobile discharges due to periodic road repairs and construction.

Analysis of risk using ecological risk index (RI) revealed that heavy metals in the examined RFs differed significantly (Fig. 2C). In all tested soil samples for Site I (control) in the studied RFs followed in the category of low ecological risks (Ei < 40). Similarly, in Site II for Balipara RF, all tested soil samples were observed in the category of low ecological risks. On the other hand, Cd and Pb were the most significant contributors to ecological risks of the examined soils in Site II of Bhomoraguri RF. Metals such as Cr, Ni, Zn, Cu, and Mn were deemed to pose a negligible environmental risk. The findings of this study are congruent with the data reported by Devi et al. (2019) over the accumulation and pollution of trace metal along roadsides in India. Vehicle exhaust fumes were reported to be the primary sources of metal pollution emitted into the environment. The findings show that national highways passing through RFs provide a possible ecological risk to forest surface soils. Vast amounts of metal contaminants are released into forest soils due to traffic emissions, which could considerably influence species diversity and productivity.

The outcome could pose a significant environmental threat. The results of the site characterization performed using the PLI revealed that Site II of both RFs ranged from somewhat unpolluted to polluted. The mean value of PLI was 0.71, followed under the unpollutincategory (PLI < 1) for Bhomoraguri RF. On the other hand, Balipara RF revealed an overall mean of 0.30, indicating unpolluted forest (Fig. 2D). The present study discovered that roads traveling through RFs might provide an eco-environmental danger for forest soil, affecting plant diversity and productivity.

Furthermore, because of their long-term buildup, high concentrations might cause pollution. Heavy metals can also pollute the environment if they accumulate and cause major environmental issues. Thus, soil metal concentrations must be monitored to minimize inappropriate accumulation.

Although the overall amounts of metals in Balipara RF were classified as of low ecological risk, this result shows that Cd and Pb were possibly polluting and environmental risk factors in the examined RFs. The independent t-test found a statistically significant difference between the two analyzed sites.

The present findings are consistent with prior research (Devi et al. 2019; Kumar et al. 2019) that found trace metal accumulation along India's roadsides and pollution and ecological hazards. According to Kumar et al. (2019), roadsides are regularly exposed to metals such as Pb, Cd, and Ni due to vehicle emissions on the national highway. Similarly, Rai et al. (2014) pointed out that vehicle traffic is one of the most significant sources of pollution, which discharges toxic elements into the environment through motor vehicle exhaust fumes, automotive and lead pipe corrosion. These contaminants may spread to other parts of the environment, with various repercussions, including reduced plant productivity. The metal uptake by plants can produce metabolic stress by preventing photosynthesis, respiration, and transpiration (Adhikari and Bhattacharyya 2015; Trombulak and Frissell 2000).

4 Plant Diversity and Tree Biomass Productivity Potential

4.1 Plant Diversity and Composition

The results on plant diversity were different between the various plant categories (i.e., grasses, forbs and trees) with the significant value of, $F_{4,123} = 13.90$, $p < 0.001$ for Bhomaraguri RF and $F_{4,119} = 18.95$, $p < 0.001$ for Balipara RF. The Shannon-Wiener index of diversity (H′) ranged from 2.08 to 4.98 in Bhomoraguri RF and from 1.81 to 3.19 in Balipara RF (Table 4). Tree species were found to have the highest diversity (H′ = 4.98) in Bhomoraguri RF, followed by forbs (H′ = 3.42), and the lowest diversity was recorded by grasses (H′ = 2.08). In Balipala RF, on the other hand, forb species had the highest diversity (H′ = 3.19) than other plant categories. Meanwhile, Sites I (control) had higher diversity than Site II for all studied plant species. For instance, tree diversity (H′) in Balipara RF was 2.70 for Sites I, while 1.81 was recorded in Site II (roadway). Based on the importance value index (IVI), the herbaceous species that recorded high domination for grasses in Site

Table 4 Diversity indices for plant species in the two studied reserve forests of Assam, India

Plant category		Forests					
		Bhomoraguri RF			Balipara RF		
	Parameters	Site I	Site II	Sig	Site I	Site II	Sig
Grasses	CD	0.117	0.133	0.334	0.126	0.134	0.697
	H′	2.342	2.081		2.171	2.083	
	J’	0.91	0.94		0.94	0.91	
Forbs	CD	0.041	0.094	0.014	0.052	0.093	0.031
	H′	3.422	2.485		3.192	2.59	
	J’	0.91	0.9		0.91	0.9	
Trees	CD	0.169	0.168	0.009	0.172	0.391	0.497
	H′	4.977	2.502		2.704	1.811	
	J’	0.72	0.53		0.51	0.73	

I were *Cynodon dactylon* (L.) Pers., *Imperata cylindrica* (Linn.) Beauv., *Brachiaria reptans* L., and *Axonopus compressus* (Sw.) P. Beauv. While forb species were *Datura stramonium* L., *Chromolaena odorata* (L.) RM., *Alternanthera sessilis* L., and *Hydrocotyle sibthorpioides* Lam. On the other hand, the roadway (Site II) was dominated by *Bidens Pilosa* L., *Euphorbia peplus* L., *Panicum virgatum* L., *D. stramonium* L., *Solanum nigrum* L., *A. donax* L., and *Oxalis corniculate* L. Furthermore, other herbaceous species such as *Leersia hexandra* Sw., *Digitaria ciliaris* (Retz.) Koeler, *Lophatherum gracile* Brongn and *Fimbristylis miliacea* (L.) Vahl., for grasses, *Persicaria strigosa* (R.Br.) Nakai., *Leucas aspera* (Willd.) Link., and *Jussiaea suffruticosa*., for forbs recorded relatively high IVI values in both sites of the studied RFs. Nevertheless, tree species that recorded relatively high IVI values in Bhomoraguri RF were *T. grandis* L.f. *Artocarpus integer* (Thunb.) Merr., *Ficus carica* L., and *Dalbergia sissoo* Roxb, while in Balipara RF, they were *Shorea robusta* Roth., *Syzygium cumini* (L.) Skeels., and *Kayea floribunda* Wall. The overall results on plant species composition and diversity (i.e., trees, grasses, and forbs) between the two studied Sites (Site I and Site II) were statistically significant ($F_{4,138}=31.18$, $p=0.000$). For the two evaluated RFs, the results revealed Site I (control) had higher species composition and diversity than Site II (roadway). The independent t-test results showed that tree species differed significantly in Bhomoraguri RF ($p=0.01$), while forbs differed significantly for both Bhomoraguri RF ($p=0.01$) and Balipara RF ($p=0.03$). However, grass differences were not statistically significant (Table 4).

The present study found that some plant species dominated more in Site II (roadway) than in Site I (control) and vice versa. The most interesting is that Site II recorded herbaceous species, which were not recorded in the forest section (Site I), indicating that other factors apart from the natural phenomenon may have attributed to the present variations. The domination of species like *A. donax L.*, *Bidens Pilosa*., and *P. virgatum* L. in Site II (roadway) of the studied RFs, are good indicators of the polluted site. These species are reported to have the ability to adapt and survive in disturbed and metal-polluted habitats (Huang et al. 2020). On the other hand, Sheng et al. (2021) highlighted that plant species richness, abundance, and distributions are function of soil characterization; species adapted to heavy metal-related soils have high richness in metal-contaminated sites.

Additionally, Huang et al. (2020) demonstrated that soil contaminated with heavy metals substantially affects plant richness by diminishing their relative density and diversity.

Thus, the abundance of such species in roadways indicates that heavy metals might have polluted the soils. Heavy metals could favour metal tolerant species over intolerant species. The small changes in plant species composition identified between the two sampled sites (roadside and forest sections) reflect the heavy metal concentrations between the two sites. Species like *Smilax ovalifolia*, *Piper betle* L., and *Lantana camara* L. have established themselves as a notorious weed that suppresses the growth and development of other understory species, particularly in Site I (control). Their weed characteristics promoted their diversity due to an excellent tolerance over environmental conditions change (Naveenkumar et al. 2017). Additionally, the decrease in species composition and diversity in Site II could be linked with frequent vegetation clearance resulting from road repair and construction. The regular vegetation clearance led to habitat fragmentation and environmental change, which could reduce the survival strategies of plant species.

4.2 Tree Biomass Productivity Potential

Twenty-four (24) dominant tree species were quantified for carbon stocking (i.e., 12 trees from each forest) to assess the impacts of the examined metal pollutants (Cd, Cr, Ni, Pb, Zn, Cu, and Mn) on tree biomass productivity potential in the forests. Two species, namely, *F. carica* and *S. robusta*, were common in both RFs. In Bhomoraguri RF, a total of 97.41 Mg ha^{-1} with an average of 8.12 ± 1.12 Mg $tree^{-1}$ ha^{-1} along with Site II (roadway) and 111.04 Mg ha^{-1} with an average of 9.25 ± 1.09 Mg $tree^{-1}$ ha^{-1} were recorded in control (Site I), (Table 5). These results were equated to 168.02 Mg ha^{-1} and 203.76 Mg ha^{-1} CO_2 sequestration by tree species in Site II and Site I, respectively. In Balipara RF, on the other hand, 89.82 Mg ha^{-1} with an average of 7.49 ± 1.85 Mg $tree^{-1}$ ha^{-1} in Site II, and 98.76 Mg ha^{-1} has recorded an average of 8.23 ± 1.90 Mg $tree^{-1}$ ha^{-1} for Site I. The CO_2 equivalent value was estimated to be 154.93 and 181.23 Mg ha^{-1} in Site II and Site I, respectively. In Site I, *T. grandis* L.f. (19.18 Mg ha^{-1}), *A. integer* (Thunb.) Merr (12.18 Mg ha^{-1}), *D. sissoo* Roxb (11.87 Mg ha^{-1}), and *F. carica* L (9.40 Mg ha^{-1}) were the tree species that produced the most biomass and carbon stocks in Bhomoraguri RF. The dominant biomass stocks in Site I and Site II of Balipara RF were *F. carica* L (11.13 and 25.20 Mg ha^{-1}), *Mimusops elengi* L (7.49 and 17.09 Mg ha^{-1}), and *Stereospermum chelonoides* DC (5.19 and 9.99 Mg ha^{-1}). The topmost biomass producer and carbon accumulator species were *T. grandis* L.f. and *F. carica* L., in Bhomoraguri and Balipara RF, respectively. Despite having slight difference in biomass production between Site I (control) and Site II (roadway), an independent sample t-test revealed that there were no significant differences ($t = 0.476$, $df = 60$, $p = 0.636$; and $t = 0.298$, $df = 82$, $p = 0.766$) for Bhomoraguri RF and Balipara RF, respectively.

The present study results demonstrate the importance of prioritizing conservation efforts for plant species that contribute significantly to biomass production. Tree species stocking, such as *T. grandis*, *A. integer*, *D. sissoo*, *F. carica*, for Bhomoraguri RF, and *M. elengi* and *S. chelonoides* for Balipara RF, provided a significant opportunity for carbon sequestration and may result in the proper implementation of carbon credits under the REDD+ program. The variations observed in biomass production among tree species could be attributed to plant diversity, positively associated with tree production and stocking (Paletto et al. 2021). Other factors such as density, basal area, forest maturation, climate, terrain, and disturbance regime (Dibaba et al. 2019) may have influenced differences in biomass production among tree species. Sheikh et al. (2020) reported that old-growth forests produced more biomass than young ones. Morever, Dibaba et al. (2019) reported factors like forest management

Table 5 Tree-wise biomass production, carbon dioxide equivalent potential (Mg $tree^{-1}$ ha^{-1}) for the two studied reserve forests

Reserved Forest	Botanical name	Family name	Site II (roadside)			Site I (control)		
			TB	TC	TCO_2 e	TB	TC	TCO_2 e
Bhomoraguri RF	*Tectona grandis* L.f.	Verbenaceae	17.33	8.15	29.89	19.18	9.59	35.20
	Artocarpus integer (Thunb.) Merr.	Moraceae	10.28	4.83	17.73	12.35	6.18	22.67
	Dalbergia sissoo Roxb.	Fabaceae	12.30	5.78	21.22	11.87	5.93	21.77
	Ficus carica L.	Moraceae	7.35	3.45	12.68	9.40	4.70	17.25
	Albizia lucidor (Steud.) I.C.Nielsen	Fabaceae	10.03	4.71	17.30	9.23	4.61	16.93
	Duabanga grandiflora (Roxb. ex DC.) W.	Lythraceae	8.39	3.94	14.47	8.52	4.26	15.63
	Dillenia indica L.	Dilleniaceae	5.57	2.62	9.61	7.61	3.81	13.97
	Shorea robusta Roth	Dipterocarpaceae	6.49	3.05	11.19	7.55	3.77	13.85
	Bombax ceiba L.	Malvaceae	5.38	2.53	9.28	7.03	3.51	12.89
	Morus laevigata Wall.	Moraceae	6.32	2.97	10.90	6.57	3.29	12.06
	Eugenia orbiculata Lam.	Myrtaceae	3.76	1.77	6.49	5.91	2.96	10.85
	Ziziphus mauritiana Lam	Rhamnaceae	4.21	1.98	7.26	5.83	2.92	10.70
		Total	97.41	45.78	168.02	111.04	55.52	203.76

Table 5 (continued)

Reserved Forest	Botanical name	Family name	Site II (roadside)			Site I (control)		
			TB	TC	TCO_2 e	TB	TC	TCO_2 e
Balipara RF	*F. carica* L.	Moraceae	23.69	11.13	40.86	25.20	12.60	46.24
	Mimusops elengi L.	Sapotaceae	15.87	7.46	27.37	17.09	8.54	31.35
	Stereospermum chelonoides DC.	Bignoniaceae	11.04	5.19	19.04	9.99	5.00	18.33
	Phyllanthus distichus Müll.Arg.	Phyllanthaceae	6.56	3.08	11.32	8.43	4.22	15.48
	Altingia excelsa L.	Altingiaceae	5.03	2.36	8.68	6.49	3.25	11.91
	S. robusta Roth	Dipterocarpaceae	5.88	2.76	10.14	6.42	3.21	11.79
	Millettia pinnata (L.) Panigrahi	Fabaceae	5.92	2.78	10.21	6.28	3.14	11.52
	Sterculia villosa Roxb. ex Sm.	Malvaceae	2.77	1.30	4.78	4.35	2.18	7.99
	Ficus elastica Roxb. ex Hornem	Moraceae	3.67	1.72	6.33	4.25	2.13	7.81
	Baccaurea ramiflora Lour.	Phyllanthaceae	2.98	1.40	5.14	3.80	1.90	6.97
	Averrhoa carambola L.	Oxalidaceae	3.57	1.68	6.16	3.31	1.66	6.08
	Castanopsis indica (Roxburgh ex Lindl.) A.	Fagaceae	2.84	1.33	4.90	3.14	1.57	5.76
		Total	89.82	42.22	154.93	98.76	49.38	181.23

TB: Tree biomass stock; TC: Tree carbon stock; TCO_2 e: Total Carbon dioxide equivalent and the allometric model influencing estimation. The finding from the present study indicates that heavy metals negatively affected tree biomass productivity potential. The buildup of heavy metals from road traffic and maintenance, in conjunction with RFs, increases the metals in soil surfaces (Siddiqui et al. 2020), which affects physiological activities. Gowd et al. (2010) reported that habitats closer to the highways are likely to accumulate heavy metals from traffic pollutants, significantly affecting their physiological process. Furthermore, Sheng et al. (2021) realized that the deposition of metals in the surface soils affects soil fertility and plant communities. As a result, we call for the necessity of monitoring levels of heavy metals on roadway crossing protected forests.

4.3 Correlation between Heavy Metals, Plant Diversity, and Tree Productivity

The degree of a relationship between heavy metals, plant diversity and tree biomass productivity potential were determined using Pearson's correlation (Table 6). The associations of heavy metal with plant diversity revealed negative relationships. The values for this correlation in Bhomoraguri RF were: Cd (r = −83%), Cr (r = −94%), Ni (r = −65%), Pb (r = −75%), Zn (r = −47%), Cu (r = −57%), Mn (r = −38%), for grass species; Cd (r = −59%), Cr (r = −74%), Ni (r = −89%), Pb (r = −66%), Zn (r = −81%), Cu (r = −81%), Mn (r = −83%) for forb species; and Cd (r = −41%), Cr (r = −55%), Ni (r = −77%), Pb (r = −51%), Zn (r = −34%), Cu (r = −29%), Mn (r = −56%) for tree species. Furthermore, the heavy metals were negatively correlated with tree biomass (TB). Their correlation coefficient matrix was found to be in the order of: TB-Pb (−80%), TB-Ni (−79%), TB-Cr (−76%), TB-Cd (−71%), TB-Cu (−67%), TB-Mn (−53%), and TB-Zn (−41%). Nevertheless, a similar trend was observed in Balipara RF (Table 6). This strong negative link with plant diversity and productivity potential demonstrate that metals have an impact on tree diversity and productivity.

The studied metals (Cd, Cr, Ni, Pb, Zn, Cu, and Mn) were positively associated. For instance, Cd-Cr (94%), Cd-Ni (74%), Cd-Pb (97%), Cu-Ni (55%), Cr-Pb (90%), Zn-Pb (43%) were among the metals that exhibited a positive connection in the correlation matrix. The significant positive association found among the metals in this study suggests that these metals have a similar origin. As stated by Siddiqui et al. (2020), this common source could be linked to vehicular emissions, as well as wear and strain on automotive parts. Gonçalves et al. (2020) discovered the impacts of Cd and Pb accumulation in various plant tissues and the resulting restrictions on material translocation. The Spearman correlation analysis between heavy metals, plant diversity, and productivity revealed that heavy metals had a significant negative impact on plant diversity, particularly on the roadside sections of the examined RFs. These findings imply that heavy metals are the primary determinants of biodiversity and productivity.

4.4 Patterns of Soil Properties, Metals, Plant Diversity, and Tree Productivity

Hierarchal cluster analysis (HCA) was employed to find the interrelationships between parameters based on their commonalities. The dendrogram given in Fig. 3 depicts soil and plant parameter clustering. HCA findings using the Ward approach and the Rescaled Distance Cluster Combined method revealed a similar pattern of heavy metal concentration. As a measure of similarity, it was possible to predict the typical patterns of metals in the analyzed soils. The HCA divided the parameters under investigation into two primary clusters (groups) for Bhomoraguri RF, each with its unique set of characteristics (Fig. 3A).

Table 6 Correlation between heavy metals with plant diversity and tree biomass productivity potential

	Cd	Cr	Ni	Pb	Zn	Cu	Mn	GD	FD	TD	TB
	Bhomoraguri RF										
Cd	1										
Cr	0.939**	1									
Ni	0.736**	0.886**	1								
Pb	0.975**	0.905**	0.757**	1							
Zn	0.835**	0.913**	0.850**	0.427**	1						
Cu	0.791**	0.916**	0.550**	0.784**	0.904**	1					
Mn	0.794**	0.901**	0.903**	0.802**	0.848**	0.891**	1				
GD	−0.826	−0.94**	−0.652	−0.75**	−0.467	−0.572	−0.385	1			
FD	−0.587**	−0.737**	−0.892**	−0.655**	−0.810**	−0.829**	−0.862**	0.084	1		
TD	−0.413**	−0.546**	−0.771**	−0.507**	−0.343**	−0.286	−0.564**	0.412	0.441	1	
TB	−0.713**	−0.763**	−0.787**	−0.801**	−0.413	−0.667	−0.528	0.930	−0.184	0.873**	1
	Balipara RF										
Cd	1										
Cr	0.892**	1									
Ni	0.927**	0.716**	1								
Pb	0.902**	0.738**	0.967**	1							
Zn	0.821**	0.601**	0.936**	0.927**	1						
Cu	0.814**	0.637**	0.912**	0.911**	0.938**	1					
Mn	0.716**	0.428**	0.823**	0.774**	0.803**	0.724**	1				
GD	−0.708*	−0.461	−0.548	−0.506	−0.263	−0. 663*	−0.612	1			
FD	−0.788**	−0.059	−0.521**	−0.440*	−0.486**	−0.522**	−0.486**	0.830**	1		
TD	−0.334	−0.288	−0.643**	−0.479**	−0.406	−0.271	−0.494	0.328	0.463	1	
TB	−0.516	−0.735**	−0.645*	−0.777**	−0.632	−0.419	−0.327	0.781**	0.965**	0.971**	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

GD: grass diversity; FD: forb diversity; TD: tree density; and TB: tree biomass productivity potential

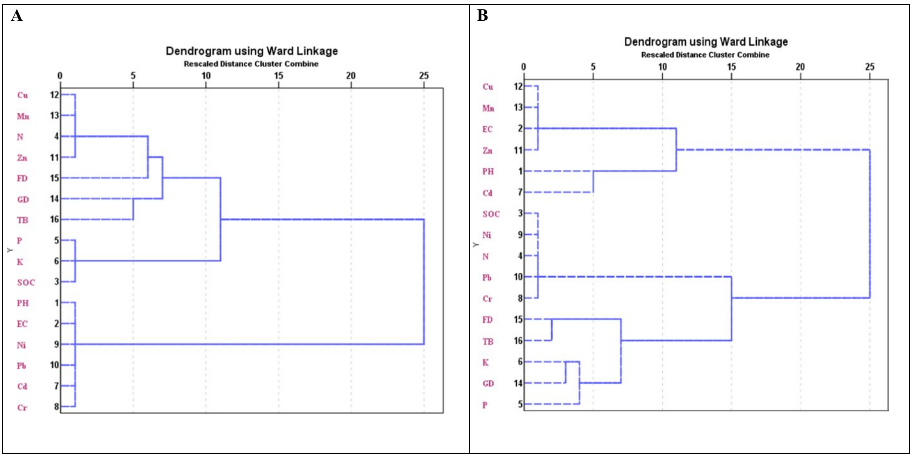

Fig. 3 Hierarchical dendrogram depicts soil physicochemical properties, heavy metal and tree biomass production clustering for Bhomotaguri RF (**A**) and Balipara RF (**B**)

Parameters such as Cu, Mn, Zn, N, Forb diversity (FD), grass diversity (GD), tree biomass production (TB), P, K, and SOC made cluster one. The second cluster contained Cr, Pb, Cd, Ni, pH, and EC. The first cluster was further divided into three sub-groups, the first sub-group included Cu, Mn, N, and Zn, while the second sub-group was made up of FD, GD, and TB, and the third sub-group had P, K, and SOC. Likewise, for Balipara RF, two main clusters were formed by HCA: the first cluster was made up of Cu, Mn, EC, Zn, pH, and Cd; and the second cluster was made up of SOC, Ni, N, Pb, Cr, FD, TB, K, GD, and P. As it was in Bhomoraguri RF, more sub-clusters were formed in Balipara RF as well (Fig. 3B). The relationship and grouping discovered in the present study support the concept that the heavy metals had similar origins, which could be strongly associated with emissions from traffic. In prior research, a similar finding was reported by Devi et al. (2019). For instance, Pb is derived chiefly from car brake pad emissions and road dust deposits (Bhuiyan et al. 2021). The variance observed in Cu, Mn, and Zn, on the other hand, suggests that these metals may have a separate source, which could be linked to agricultural activities occurring near the studied RFs. Previous research has related the concentration and sources of heavy metals in soils to human activities, particularly agriculture and industrial waste (Bhuiyan et al. 2021; Chen et al. 2021).

4.5 Predicting the Effects of Heavy Metals on Tree Biomass Productivity Potential

A stepwise regression analysis was performed to estimate the impacts of heavy metal (Cd, Cr, Ni, Pb Cu, Mn and Zn) on tree biomass productivity potential (Table 7). The findings revealed that these metals accounted for 74% of the variations in tree biomass productivity potential. Metal concentrations in surface soils have a variable percentage of effects on tree biomass productivity potential. The uniqueness contributions of each metal (predictors) were significant for Cd ($\beta = 1.94$, $t = 2.56$, $p = 0.015$); and Cr ($\beta = 8.23$, $t = -2.69$, $p = 0.001$); but not for Ni ($\beta = -0.34$, $t = -1.32$, $p = 0.198$); Zn ($\beta = -0.16$, $t = -0.61$, $p = 0.55$); Cu ($\beta = -0.25$, $t = -0.70$, $p = 0.49$); Mn ($\beta = 0.11$, $t = 1.35$, $p = 0.73$); and Pb ($\beta = -0.49$, $t = -1.88$, $p = 0.07$). The overall regression models revealed a strong negative relationship between metals and tree biomass productivity potential, with linear

Table 7 Stepwise regression analysis to predict the effects of heavy metals on tree biomass production

Model	Predictors	Regression equations	R Square	Sig
1.	Cd	$\hat{Y}=36.\ 478+(5.12\times Cd)$	$R^2=0.62$	$p<0.001$
2.	Cr	$\hat{Y}=34.488$ - $(1.178\times Cr)$	$R^2=0.64$	$p<0.001$
3.	Ni	$\hat{Y}=43.690$ - $(0.161\times Ni)$	$R^2=0.63$	$p<0.001$
4.	Pb	$\hat{Y}=42.590$ - $(0.249\times Pb)$	$R^2=0.66$	$p<0.001$
5.	Zn	$\hat{Y}=10.49$ - $(0.045\times Zn)$	$R^2=0.55$	$p<0.001$
6.	Cu	$\hat{Y}=10.49$ - $(0.094\times Cu)$	$R^2=0.57$	$p<0.001$
7.	Mn	$\hat{Y}=10.49$ - $(0.003\times Mn)$	$R^2=0.54$	$p<0.001$
8.	$Cd\times Cr$	$\hat{Y}=36.478+(5.12\times Cd)$ - $(1.178\times Cr)$	$R^2=0.63$	$p<0.001$
9.	$Ni\times Pb$	$\hat{Y}=43.690$ - $(0.161\times Ni)$- $(0.249\times Pb)$	$R^2=0.66$	$p<0.001$
10.	$Zn\times Cu\times Mn$	$\hat{Y}=10.49$ - $(0.045\times Zn)$ - $(0.094\times Cu)+(0.003\times Mn)$	$R^2=0.66$	$p<0.001$
11.	$Cd\times Cr\times Ni\times Pb\times Zn\times Cu\times Mn$	$\hat{Y}=36.478+(5.12\times Cd)$ - $(1.178\times Cr)$ - $(0.161\times Ni)$ - $(0.249\times Pb)$ - $(0.045\times Zn)$ - $(0.094\times Cu)+(0.003\times Mn)$	$R^2=0.\ 74$	$p<0.001$

models: $\hat{Y}=36.\ 478+5.12\times Cd$, $R^2=0.62$, $p<0.001$; $\hat{Y}=34.488–1.178\times Cr$, $R^2=0.64$, $p<0.001$; $\hat{Y}=43.690$ - $0.161\times Ni$, $R^2=0.63$, $p<0.001$; $\hat{Y}=42.590–0.249\times Pb$, $R^2=0.66$, $p<0.001$; $\hat{Y}=10.49–0.045\times Zn$, $R^2=0.55$, $p<0.001$; $\hat{Y}=10.49–0.094\times Cu$, $R^2=0.57$, $p<0.00$; and $\hat{Y}=10.49–0.003\times Mn$, $R^2=0.54$, $p<0.001$. While the overall model was: $\hat{Y}=36.478+5.12\times Cd$ – $(1.178\times Cr)$ – $(0.161\times Ni)$ – $(0.249\times Pb)$ – $(0.045\times Zn)$ – $(0.094\times Cu)+(0.003\times Mn)$, for Cd, Cr, Ni, Pb, Zn, Cu and Mn, respectively.

The studied heavy metals have shown almost similar impacts on tree biomass productivity. Their Adjusted R^2 values ranged from 54% for minimum and 66% for maximum. The great contribution of Pb (66%) reflects its concentration and ecological risks observed in this study. The large concentration of Pb in surface soils along the roadway could be linked to inhibition of plant physiological activities, including photosynthesis, which is a primary activity on their productivity. Singh et al. (2020) reported that heavy metals tend to modify the physicochemical characteristics of soils, affecting plant production. Thus, the accumulations of metals like Mn, Cd, Ni, and Cd in surface soils along roadway (Site II) might have caused significant change of soil physical and chemical properties, leading to change in the normal absorption potential of nutrients. As a result, plant growth and stocking potential become affected due to the absorption of more heavy metals than other required plant nutrients. However, differences in sources and discharge modality of these heavy metals from vehicles could have been attributed to the variation among metals. In addition, the correlation analyses in the present study showed a significant correlation for metals with each other (Table 6), suggesting that they originate from common sources. The commonality observed in these metals is typically reflected in their similar impact on tree biomass productivity.

5 Conclusions

The following findings could be drawn from the present study:

i. Despite the fact that the mean concentrations of all the examined heavy metals (Cd, Cr, Ni, Pb, Zn, Cu, and Mn) were within acceptable limits of the Indian standards guideline for natural soils, soil samples collected from Site II (roadway) had relatively higher levels of heavy metal concentration than soil samples from Site I (control). The result suggests that the primary sources of these metals were automotive discharges from vehicular emissions. The national highway (NH-15), which runs through the Bhomoraguri and Balipara reserve forests (RFs), significantly contributed to these heavy metals in surface soils. Thus, these metals in RFs must be monitored so that their accumulation and toxicity would not affect the forest ecosystem. It is important to develop a database for heavy metal concentrations in soils along roadways that run through protected areas and their potential ecological risk on the forest-based ecosystem.
ii. Ecological risk assessment results indicated that Mn, Cd, and Pb were the sources of increased environmental danger, contributing to pollution, contamination, and ecological risks in forest surface soils of these reserve forests.
iii. The correlation matrix revealed a negative link between heavy metals and tree productivity potential. The strong negative association observed suggests that metals are the most important parameters impacting plant diversity and tree biomass production. Furthermore, cluster analysis also corresponded with the grouping of variables, proving that the analyzed metal contaminants have similar sources of enrichment in surface soils. There is a need for a detailed study on pollution mechanisms and metal distribution among forest ecosystems. Thus, environmentalists and decision-makers should prioritize prevention strategies to reduce this eco-environmental impact.

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Code Availability Non-applicable.

Declarations

Competing Interests The authors declare that they have no known competing financial or personal interests.

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