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Phytosociological and Abiotic Factors Influencing the Coverage and Morphological Traits of the Invasive Alien *Potentilla indica* (Rosaceae) in Riparian Forests and Other Urban Habitats: A Case Study from Kraków, Southern Poland

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Abstract: Biological invasions are considered one of the most important threats to biodiversity worldwide, and their intensity increases with urbanization. *Potentilla indica*, a perennial stoloniferous plant of Asian origin, is a newly emerging invasive alien species in European cities and other areas. Due to its wide ecological range, it may threaten many native species, especially in urban riparian forests which are particularly susceptible to plant invasions. Although it shows high phenotypic plasticity, its coverage and morphological variability depending on the type of vegetation and abiotic factors in natural conditions have not been studied so far. Therefore, in this study, we aimed to explore this issue, using phytosociological relevés and measurements of selected environmental factors and morphological features of *P. indica* in Kraków, the second largest city in Poland, central Europe. We demonstrated that the coverage and morphological traits of *P. indica* can be significantly affected by the type of plant community, and the presence and abundance of the species in urban habitats are strongly related to soil moisture, electrical conductivity, and fertility. We also found that the coverage of *P. indica* is positively correlated with the Evenness index, height of herbaceous layer, soil electrical conductivity and moisture, and negatively with the number of species, soil compactness, and phosphorus content in the soil. We further revealed that the size of the leaves and the length of the pedicels and stolons in *P. indica* can be positively influenced by its coverage. To prevent the invasion of *P. indica* in riparian forests and other urban habitats, we suggest controlling its cultivation and disposal, removing new appearances, and maintaining high species diversity with a dominance of one or a few native species in plant communities.

Keywords: clonal plants; Ellenberg's indicator values; plant invasion; phytosociological assessment; soil quality; urban ecology

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1. Introduction

The invasion of alien plant species in cities is a global phenomenon which intensifies with urbanization [1–3]. Urban floras are usually rich in alien species due to the intentional introduction of non-native plants for horticulture as well as their unintentional introduction through transport [1,4–6]. However, the share of alien plant species in cities depends mainly on climatic and habitat conditions [1,4,7]. Above all, numerous environmental disturbances and strong propagule pressure observed in urban areas favor the naturalization and invasion of non-native plants [6]. Moreover, in expanding cities, the high shape complexity of highly disturbed habitats may increase the exchange surface that alien plants use to spread their propagules across the landscape mosaics, significantly contributing to their invasion [8].

The expansion of cities, on the one hand, entails the need to preserve the remnants of natural ecosystems and, on the other hand, requires the creation of new green areas that are crucial for maintaining wildlife [9] and ensuring the physical and mental health of city residents [10,11]. Along with ecological, economic, and social functions, alien plant species are commonly cultivated in urban green areas because of their resistance to drought, high temperatures, and air and soil pollution [2,12,13]. Generally, horticulture is considered the main source of naturalized plant species, and many exotic plants can easily escape from cultivation or enter natural habitats through illegal disposal of garden waste containing their propagules [12,14,15]. Therefore, special control is recommended when growing and disposing alien plant species, especially those already considered invasive or potentially invasive [16].

Potentilla indica (Andrews) Th. Wolf (in P.F.A.Ascherson and K.O.R.Graebner, Syn. Mitteleur. Fl. 6(1): 661 (1904)), a perennial plant of the family Rosaceae, is native to south and south-eastern Asia, although it has been introduced to almost all other continents except Antarctica [17–20]. As an ornamental and ground cover plant, it is particularly valued in urban gardening [21]. Unfortunately, it easily escapes from cultivation and naturalizes in semi-natural and anthropogenic habitats [18,22–25]. Moreover, it is considered invasive in some cities of Europe [26–29]. In its native range, *P. indica* occurs on mountain slopes (below 3100 m), meadows, riverbanks, and wet places, while in its secondary range, it is usually found in lowlands, in neglected gardens, parks, cemeteries, walls, lawns, roadsides, as well as in ruderal thickets and disturbed riparian forests [17,18,23,24,27].

The invasiveness of *P. indica* in urban areas is insufficiently recognized; however, its negative ecological impact consists mainly of rapid growth and dense patch formation that reduce the population size and species richness of native plants [27,28]. Moreover, some researchers suggest it is more competitive in moist and nitrogen-rich habitats [26,30]. Interestingly, the achenes of *P. indica* are often carried on shoes or dispersed by synanthropic birds from the thrush family, accelerating its spread in urban and suburban areas [24,25,27]. Furthermore, the proximity of cities and the presence of paths and roads were proven to favor the entry of *P. indica* into forests, particularly in warmer parts of forests, in north-eastern Slovenia [29]. Generally, the establishment of *P. indica* in central Europe is related to mean annual temperature and it occurs mainly in lowland regions with a mild climate [23].

Due to its wide ecological range, *P. indica* may threaten many native species, especially in urban riparian forests, which are particularly susceptible to plant invasions [31–33]. Nevertheless, it is not known how the coverage and morphological characteristics are shaped in *P. indica* depending on the plant community it colonizes, albeit the plant is considered to exhibit high phenotypic plasticity [34]. Moreover, there are no studies that would show the influence of abiotic factors on the coverage and morphological diversity of *P. indica* in the wild, apart from experimental studies. Therefore, in this study, we focused on the effect of phytosociological and abiotic factors on the coverage and morphological features of *P. indica* in urban forests and other habitats. Specifically, we asked:

(1) How the type of vegetation, species diversity, and height of the herbaceous layer affect the coverage and morphological features of *P. indica*;
(2) How the coverage and morphological characteristics of *P. indica* depend on light intensity and soil conditions (moisture, electrical conductivity, compactness, pH, and content of nutrients);
(3) Whether the increasing cover of *P. indica* enhances its morphological features.

2. Materials and Methods

2.1. Study Species

Taxonomic treatment of *P. indica* followed Plants of the World Online [20]. Until recently, the plant was known as *Duchesnea indica* (Jacks.) Focke; however, molecular phylogenetic studies have proven that *Duchesnea* Sm. is nested in the genus *Potentilla*

L. [25]. *P. indica* is a clonal herb with short rhizome and long stolons (30–100 cm) that form plantlets at nodes. It is often confused with wild strawberries (*Fragaria* L. spp.) due to the similar aggregate fruit and 3-foliate leaves, although it produces solitary and yellow flowers [17], Figure 1A,B.

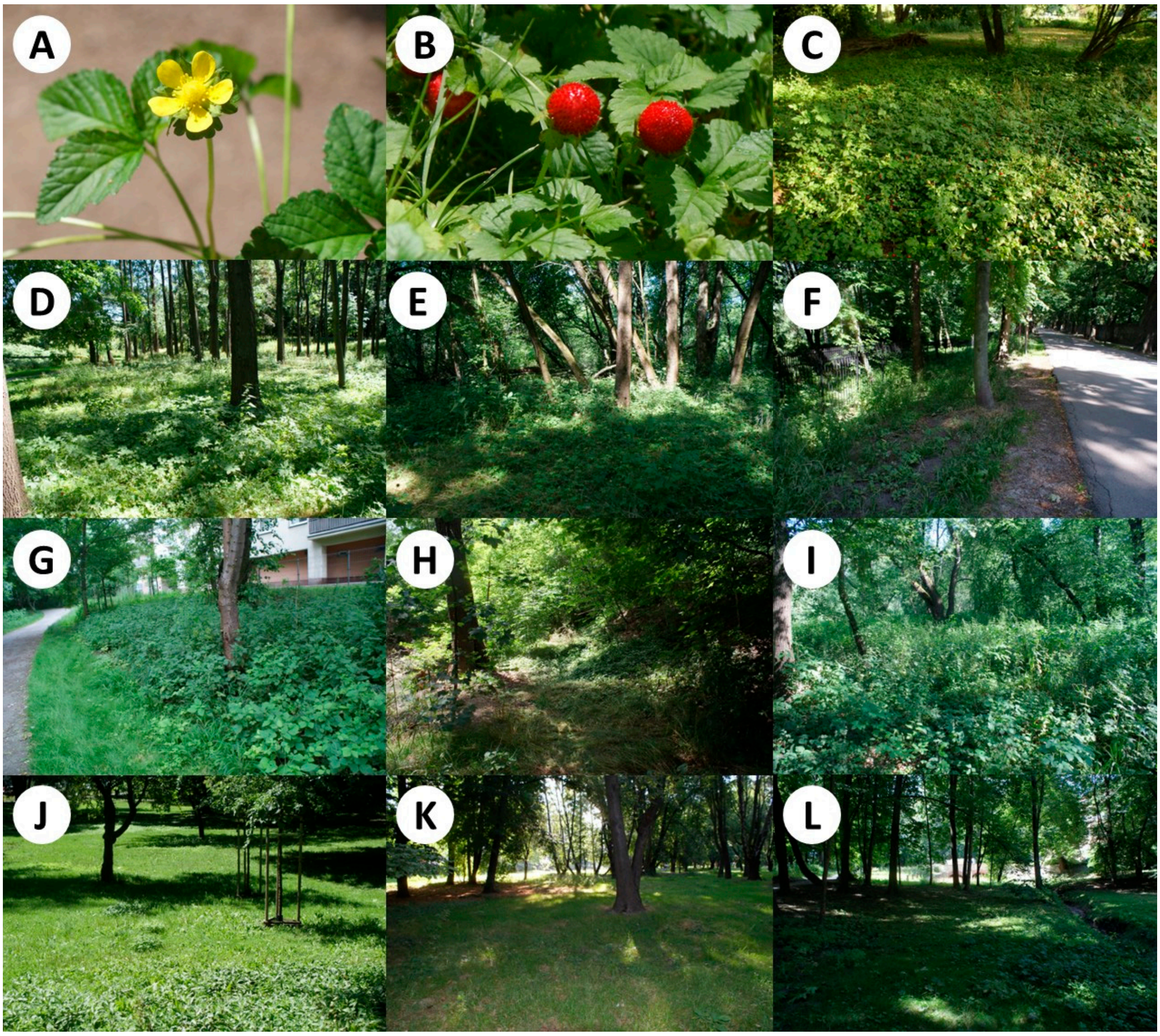

Figure 1. Morphological details of *Potentilla indica* and vegetation of study sites in Kraków, southern Poland: (**A**)—flowering shoot, (**B**)—fruiting shoots, (**C**)—Polish Aviators' Park at Aleja Pokoju Street, (**D**)—Dąbie Park, (**E**)—Melchiora Wańkowicza Street, near Dłubnia River, (**F**)—Aleja Waszyngtona Street, (**G**)—Biskupa Filipa Padniewskiego Street, (**H**)—Podrzecze Street, near Dłubnia River, (**I**)—Wilga River Park, (**J**)—Florian Nowacki Planty Park, (**K**)—Stanisław Skalski Park, and (**L**)—Decius Park (Photographed by A. Pliszko).

2.2. Study Area

The study was conducted in Kraków, the second largest city in Poland, central Europe, in 2022. It lies in a temperate climate zone and covers an area of 327 km^2, with a population of 803.3 thousand [35]. From 1991 to 2020, the average annual air temperature and annual precipitation in Kraków were 8.9 °C and 673 mm, respectively [35].

In Poland, *P. indica* is considered a rare and locally established alien species [36,37]. The first spontaneous occurrence of *P. indica* in Kraków was recorded in the 1970s, in the Botanical Garden of the Jagiellonian University [38]. In the early 21st century, it was assessed as a plant that easily escapes from cultivation in the city [39], although, the exact time of its establishment remains unknown. Currently, it can be found in many places throughout the city, such as parks, lawns, roadsides, hedges, ruderal thickets, and forests, acting as an invasive species.

The study included 10 representative sites differing in vegetation and abundance of *P. indica* (Table S1, Figures 1C–L and 2). At each site, a transect covering 10 square plots (5 m × 5 m) was established (Figure 2B). The GPS coordinates and altitude of study plots were recorded using a GARMIN GPSMAP 62st (Garmin (Europe) Ltd., Southampton, UK).

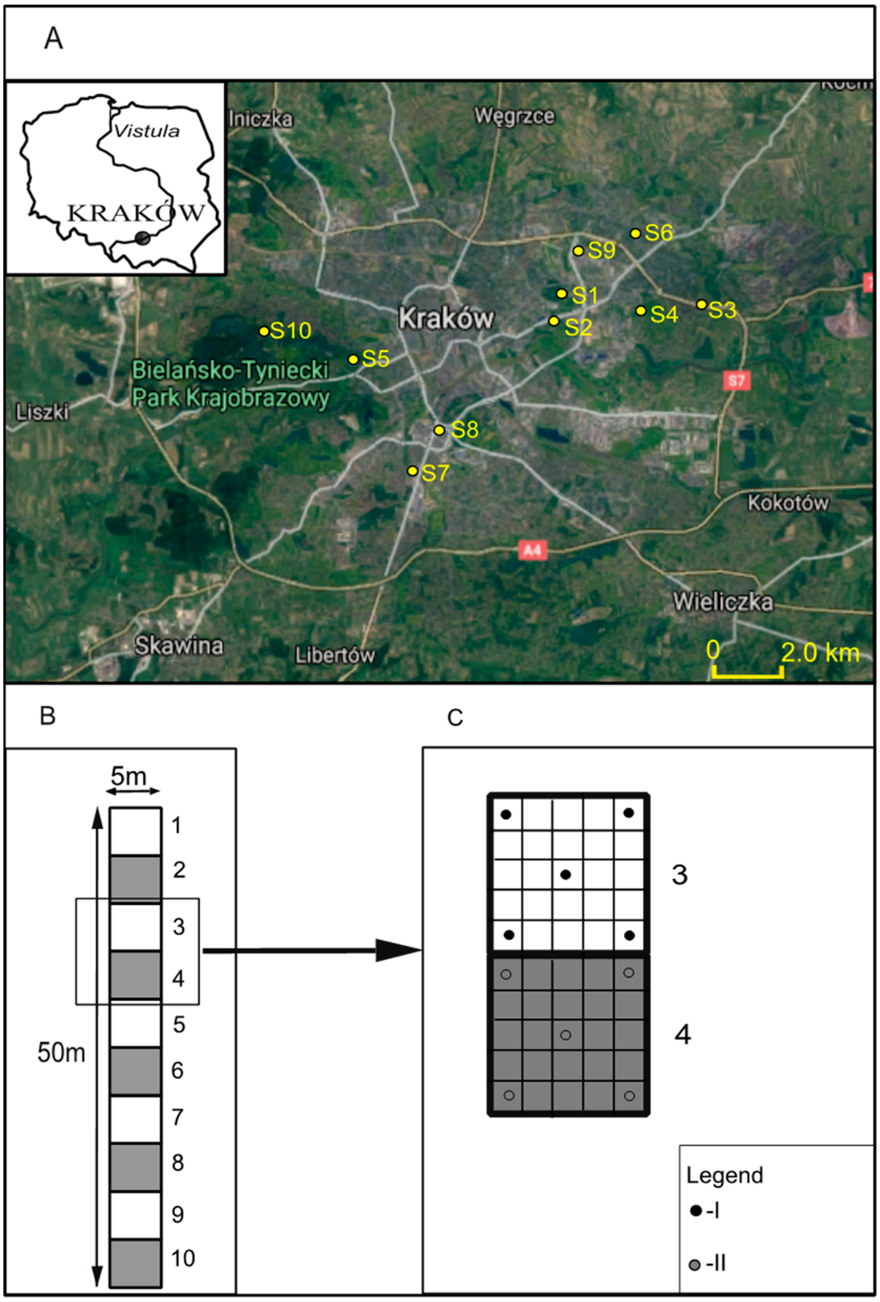

Figure 2. Distribution of study sites (S1–S10) in Kraków, southern Poland (**A**), distribution of study plots (1–10) within transect (**B**), and sampling scheme within plots (**C**). I and II indicate sampling points of environmental parameters within 5 m-squares. Gray color indicates even-numbered plots in which soil samples were collected for chemical analyses.

2.3. Phytosociological Analysis

In each study plot, a phytosociological relevé was made using the Braun-Blanquet method [40]. Within the plots, the cover-abundance of vascular plant species was visually estimated using a six-degree scale, and the percentage of total vegetation cover in tree, shrub, herb, and moss layers was visually estimated with an accuracy of 5%. Moreover, the height of the tallest plant in the herb layer (undergrowth) in each plot was measured using a folding ruler (StabilaMessgeräte Gustav Ullrich GmbH, Annweiler, Germany) with an accuracy of 0.1 cm.

100 phytosociological relevés were subjected to numerical-hierarchical classification based on species quantity. The similarity between the plots was calculated using the Ružička formula for quantitative data (a value of 0.5 was taken for +). The analysis was based on the weighted pair group method using arithmetic averages (WPGMA) [41]. The classification was performed using the SYN-TAX 2000 package [42]. Moreover, within the distinguished groups, phytosociological stability, and cover coefficient were calculated for each species. The coverage ratio was calculated by converting degrees of abundance into "average percent coverage" (r—0.1%, +—0.5%, 1—5%, 2—17.5%, 3—37.5%, 4—62.5%, and 5—87.5%) [43] and calculating the average value per syntaxon. The nomenclature of vascular plant species was adopted from Plants of the World Online [20]. The affiliation of species to syntaxonomic units followed Matuszkiewicz [44]. Diversity and quantitative relationships between species in the study sites were calculated based on the Shannon–Wiener diversity index [45], Evenness index [46], and Simpson index [47]. Furthermore, habitat conditions were characterized based on Ellenberg's indicator values [48] using the JUICE program [49], and the average values of the following indicators were calculated for the distinguished plant communities: light (L), temperature (T), continentality (K), moisture (F), reaction (R), and nutrients (N).

2.4. Measurement of Abiotic Factors

In each study plot, the light intensity in the herb layer, soil moisture, soil electrical conductivity, and soil compactness were measured in five repetitions, at five sampling points (Figure 2C), using the LX-10 (Voltcraft, Conrad Electronic SE, Hirschau, Germany) digital light meter (0–199900 lx), Bioogród (Browin, Łódź, Poland) soil tester (0–3 dry soil, 4–7 moist soil, and 8–10 wet soil), HI98331 (Hanna Groline, Hanna Instruments, Olsztyn, Poland) direct soil electrical conductivity meter (0.00–4.00 mS/cm), and AGRETO soil compaction tester (AGRETO electronics GmbH, Raabs, Austria), respectively. The soil compactness was understood as the depth at which the compacted soil layer begins from the top of the soil (the deeper the penetrometer probe goes, the less compact the soil). Moreover, a soil sample was taken in every second plot of the transect at each study site. The soil sample (about 500 g) was made by mixing five small soil samples (about 100 g) taken from five sampling points within the plot (Figure 2C). A total of 50 soil samples (five per study site) were taken from the top layer of the soil (a depth of up to 10 cm) using a stainless-steel soil spatula and placed in plastic bags. In the laboratory, the soil samples were dried at room temperature, sieved (using a 2 mm sieve), and subjected to chemical analysis. The soil pH and the content of phosphorus, potassium, nitrate, and ammonium nitrogen were determined using a VISOCOLOR® kit (Macherey-Nagel, Düren, Germany).

2.5. Morphometric Analysis

The morphometric analysis of *P. indica* was based on fresh plant materials, including 10 or fewer mature individuals (maternal ramets) with developed flowers or fruits per plot. The following morphological features of maternal ramets were included in the measurements: length of the longest petiole (PTL), length (LL) and width (LW) of the leaf blade (leaf with the longest petiole), number of stolons (SN), length of the longest stolon (LSL), number of daughter ramets on the longest stolon (DRN), length of the longest pedicel (PDL), and length (FL) and width (FW) of fruit. In some cases, daughter ramets produced their stolons, but these stolons were not included in the number of stolons of the maternal ramet. The morphological features were measured using a self-retracting tape (Dedra M582, Pruszków, Poland) with an accuracy of 0.1 cm.

2.6. Statistical Analysis

The normal distribution of the untransformed data was tested using the Kołmogorov–Smirnov test, and the homogeneity of variance was verified using the Levene test at the significance level of $p < 0.05$. The Kruskal–Wallis H test with the Bonferroni correction to adjust probability $p < 0.0017$ was applied to check the statistical significance of differences in Ellenberg's indicator values, Shannon-Wiener, Evenness, and Simpson indices, light intensity, the height of the herbaceous layer, soil moisture, soil electrical conductivity and the depth of the compact soil layer, soil pH, the content of phosphorus, potassium, nitrate, and ammonium nitrogen, the coverage and morphological features of *P*. *indica* between the groups of plant communities. The Mann–Whitney U test was used to check the statistical significance of differences in the light intensity, soil electrical conductivity, soil pH, and the content of phosphorus, potassium, nitrate, and ammonium nitrogen in the soil between the plots with and without *P. indica*. Also, the *t*-Student test was applied to check the statistical significance of differences in the height of the herbaceous layer, the soil moisture, and the depth of the compact soil layer between the plots with and without *P. indica*.

The Pearson coefficient was used to test the correlations between the coverage and morphological features of *P. indica* and the Shannon-Wiener, Evenness and Simpson indices, light intensity, height of the herbaceous layer, soil moisture, soil electrical conductivity, and the depth of the compact soil layer. The Spearman coefficient was applied to check the correlations between the coverage and morphological features of *P. indica* and soil pH and the content of phosphorus, potassium, nitrate, and ammonium nitrogen. Moreover, the Pearson coefficient was used to test the correlations between the coverage and the morphological features of *P. indica*. The mean values of environmental parameters and morphological traits were included in correlation tests. Statistical analysis was performed using a Statistica package (version 13.3).

3. Results

3.1. Characteristics of Plant Communities

Based on the numerical classification of phytosociological relevés, eight groups of plant communities were distinguished (Figure S1). Interestingly, each group corresponds to one or two study, sites and the plots in which *P. indica* was absent (N = 35) do not form one separate group. Although the species composition of plant communities varied at the study sites, ruderal species from the *Artemisietea vulgaris* class dominated in groups 1 and 2, forest species from the *Querco-Fagetea* class prevailed in groups 3, 4 and 5, and meadow species from the *Molinio-Arrhenatheretea* class had the largest share in the remaining groups (Table S2).

In group 1, with the community *Potentilla indica-Geum urbanum*, *P. indica* achieved the highest degree of stability and the greatest coverage, while in group 2, with the community *Urtica dioica-Rubus caesius*, it occurred sporadically. In group 3, with the community *Galeobdolon luteum-Elymus caninus*, *P. indica* achieved degree IV of stability and significant coverage. In group 4, with the community *Festuca gigantea-Galeobdolon luteum*, *P. indica* occurred sporadically. In group 5, with the community *Fraxinus excelsior-Aegopodium podagraria*, *P. indica* showed the highest degree of stability but had low coverage. In group 6, with the community *Agrostis capillaris-Poa trivialis*, *P. indica* achieved degree IV of stability and significant coverage. In group 7, with the association, *Lolio-Polygonetumarenastri*, *P. indica* showed degree III of constancy and the lowest cover coefficient. It was dominated by meadow species adapted to trampled places. In group 8, with the community *Agrostis capillaris-Viola odorata*, *P. indica* achieved degree IV of stability and significant coverage (Table S2).

The groups differed significantly in the number of species, the Shannon-Wiener index, the height of the herbaceous layer, and the coverage of *P. indica* (Tables 1, 2 and S3). On the other hand, there was no significant difference in the Evenness and Simpson indices between the groups (Tables 1 and S3).

Table 1. Number of species, Shannon-Wiener index, Evenness index, Simpson index and Ellenberg's indicator values (mean ± SD) in groups of phytosociological plots. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with the Bonferroni correction); ^{ns}—not significant. Significant values of the H Kruskal–Wallis test results of multiple comparisons between particular groups are given in Tables S3 and S4.

Group	Number of Species	Shannon-Wiener Index [H′]	Evenness Index [J′]	Simpson Index [SIMP]	Ellenberg's Indicator Values					
					Light	Temperature	Continentality	Moisture	Reaction	Nutrients
1	10.00 (±3.26)	1.77 (±0.40)	0.78 (±0.10)	0.75 (±0.11)	5.35 (±0.38)	5.44 (±0.23)	4.03 (±0.51)	5.90 (±0.32)	7.02 (±0.27)	7.18 (±0.33)
2	17.20 (±3.01)	2.14 (±0.32)	0.76 (±0.10)	0.79 (±0.09)	6.03 (±0.31)	5.62 (±0.20)	4.17 (±0.50)	6.00 (±0.31)	7.16 (±0.32)	7.37 (±0.39)
3	12.95 (±3.09)	1.84 (±0.45)	0.72 (±0.15)	0.73 (±0.15)	5.07 (±0.37)	5.37 (±0.27)	3.82 (±0.47)	5.74 (±0.43)	6.91 (±0.13)	6.92 (±0.48)
4	16.00 (±1.56)	2.21 (±0.32)	0.80 (±0.11)	0.82 (±0.09)	4.71 (±0.30)	5.40 (±0.22)	3.96 (±0.42)	5.63 (±0.32)	6.63 (±0.29)	6.42 (±0.24)
5	12.70 (±5.95)	1.66 (±0.48)	0.67 (±0.09)	0.69 (±0.12)	5.44 (±0.29)	5.22 (±0.17)	3.13 (±0.13)	6.02 (±0.30)	6.57 (±0.48)	6.95 (±0.57)
6	22.80 (±3.79)	2.57 (±0.24)	0.83 (±0.09)	0.85 (±0.06)	5.32 (±0.81)	5.46 (±0.13)	3.48 (±0.14)	5.64 (±0.26)	5.94 (±0.38)	5.99 (±0.47)
7	13.50 (±1.72)	2.01 (±0.26)	0.77 (±0.07)	0.79 (±0.07)	7.03 (±0.31)	5.60 (±0.24)	3.16 (±0.19)	5.27 (±0.11)	6.39 (±0.55)	6.54 (±0.26)
8	21.30 (±5.19)	2.40 (±0.28)	0.79 (±0.06)	0.82 (±0.06)	6.41 (±0.29)	5.58 (±0.22)	3.28 (±0.20)	5.48 (±0.14)	5.92 (±0.64)	6.31 (±0.60)
Kruskal–Wallis H test	59.15 *	38.67 *	13.31 ^{ns}	18.97 ^{ns}	67.31 *	22.70 ^{ns}	55.04 *	40.52 *	62.83 *	51.43 *

Table 2. Coverage of *Potentilla indica* and environmental parameters (mean ± SD) in groups of phytosociological plots. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with the Bonferroni correction); ^{ns}—not significant. Significant values of the H Kruskal–Wallis test results of multiple comparisons between particular groups are given in Table S5.

Group	Coverage of *P. indica*	Light Intensity [cd × sr/m^2]	Depth of Compact Soil Layer [cm]	Soil Electrical Conductivity [mS/cm]	Soil Moisture [0–10]	Height of Herbaceous Layer [cm]	Soil pH	Content of Nitrate [mg/kg]	Content of Amonium Nitrogen [mg/kg]	Content of Potassium [mg/kg]	Content of Phosphorus [mg/kg]
1	2.57 (±1.77)	5339.08 (±9311.79)	28.69 (±8.94)	0.41 (±0.19)	7.47 (±2.07)	67.85 (±23.07)	6.24 (±0.24)	190.00 (±39.44)	1.00 (±2.11)	2.56 (±3.29)	2.40 (±2.67)
2	0.40 (±0.84)	2622.58 (±1853.81)	12.42 (±6.47)	0.08 (±0.02)	2.44 (±0.87)	69.83 (±14.25)	6.38 (±0.16)	170.00 (±67.08)	3.00 (±4.47)	12.50 (±4.69)	8.80 (±5.22)
3	0.93 (±1.23)	4998.65 (±7658.86)	36.58 (±13.22)	0.29 (±0.11)	6.70 (±1.10)	57.64 (±9.41)	6.15 (±0.34)	202.50 (±78.57)	3.00 (±4.83)	7.42 (±3.51)	2.80 (±2.66)
4	0.40 (±0.84)	4055.18 (±3349.25)	30.88 (±7.70)	0.22 (±0.06)	4.96 (±1.17)	59.56 (±24.67)	6.50 (±0.00)	130.00 (±67.08)	0.00 (±0.00)	0.90 (±1.24)	7.00 (±3.16)
5	0.83 (±0.76)	8021.12 (±13,398.74)	20.61 (±9.17)	0.25 (±0.09)	5.73 (±1.58)	49.89 (±13.39)	6.40 (±0.22)	200.00 (±70.71)	0.00 (±0.00)	2.70 (±3.11)	5.40 (±0.89)
6	0.92 (±1.08)	11,607.84 (±10,272.79)	15.57 (±9.33)	0.36 (±0.13)	6.37 (±1.64)	43.07 (±27.46)	6.50 (±0.00)	160.00 (±82.16)	0.00 (±0.00)	4.38 (±1.63)	5.80 (±1.79)
7	0.24 (±0.40)	24,152.14 (±26,253.31)	11.03 (±2.21)	0.24 (±0.06)	6.01 (±0.97)	19.50 (±4.01)	6.30 (±0.45)	220.00 (±75.83)	3.00 (±4.47)	3.28 (±1.34)	7.00 (±1.41)
8	1.02 (±0.92)	7282.02 (±5937.08)	14.61 (±7.38)	0.08 (±0.03)	3.59 (±1.10)	27.70 (±9.18)	6.00 (±0.00)	130.00 (±44.72)	11.00 (±8.94)	6.58 (±4.65)	1.40 (±0.55)
Kruskal–Wallis H test	27.73 *	15.44 ^{ns}	54.30 *	50.04 *	52.97 *	49.30 *	18.40 ^{ns}	10.33 ^{ns}	16.04 ^{ns}	26.91 *	25.48 ^{ns}

3.2. Characteristics of Abiotic Conditions

The groups differed significantly in Ellenberg's indicator values, except temperature (Tables 1 and S4) as well as in the depth of the compacted soil layer, soil electrical conductivity, soil moisture, and potassium content (Tables 2 and S5). On the other hand, there were no significant differences in the light intensity, soil pH and the content of nitrate, ammonium nitrogen, and phosphorus between the groups (Tables 2 and S5). Moreover, the plots with *P. indica* were characterized by significantly higher soil electrical conductivity, soil moisture, and content of nitrate, as well as by significantly lower content of ammonium nitrogen, potassium, and phosphorus (Figure 3).

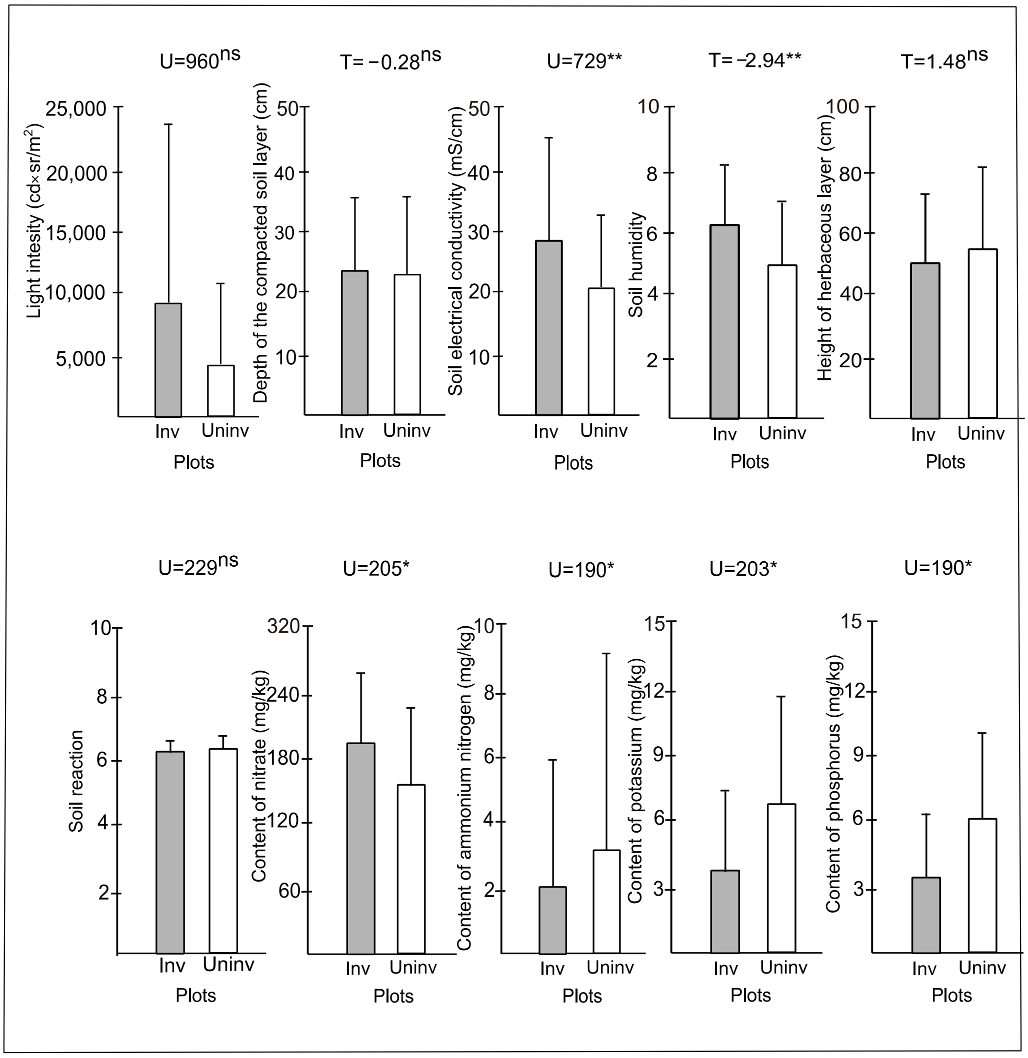

Figure 3. Differences in environmental parameters between the plots invaded (Inv, gray bars) and uninvaded (Uninv, white bars) by *Potentilla indica*. Mean (±SD) values are presented. Asterisks indicate the level of statistical significance: * $p \leq 0.05$; ** $p < 0.01$; ^{ns}—not significant.

3.3. Morphological Variability of *P. indica* in Various Plant Communities

The morphological traits of *P. indica* differed significantly between the groups of plant communities. In most cases, the highest values of morphological features were recorded in groups 1 and 2, and the lowest in group 7 (Tables 3 and S6).

Table 3. Morphological features of *Potentilla indica* (mean ±SD) in groups of phytosociological plots. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with Bonferroni correction);. Significant values of the H Kruskal–Wallis test results of multiple comparisons between particular groups are given in Table S6.

Group	N	Length of Pedicel [cm]	Length of Petiole [cm]	Width of Leaf [cm]	Length of Leaf [cm]	Number of Stolons	Length of the Longest Stolon	Number of Daughter Ramtes	N	Length of Fruit [cm]	Width of Fruit [cm]
1	152	11.72 (±3.57)	16.88 (±4.01)	7.19 (±1.39)	6.34 (±1.38)	2.78 (±1.48)	79.65 (±29.88)	6.88 (±1.73)	152	1.16 (±0.23)	1.40 (±0.30)
2	20	10.33 (±3.09)	15.34 (±3.38)	8.13 (±1.41)	7.39 (±1.24)	3.70 (±1.26)	78.60 (±23.97)	8.25 (±1.37)	20	1.18 (±0.09)	1.58 (±0.17)
3	103	9.97 (±4.30)	16.69 (±4.82)	7.59 (±1.77)	6.74 (±1.62)	2.89 (±1.28)	89.80 (±41.78)	8.66 (±2.45)	37	1.00 (±0.16)	1.14 (±0.21)
4	20	6.13 (±1.81)	8.96 (±2.47)	5.74 (±1.07)	5.00 (±0.96)	2.25 (±1.02)	43.51 (±20.98)	6.60 (±1.96)	20	1.08 (±0.12)	1.34 (±0.16)

Table 3. *Cont.*

Group	N	Length of Pedicel [cm]	Length of Petiole [cm]	Width of Leaf [cm]	Length of Leaf [cm]	Number of Stolons	Length of the Longest Stolon	Number of Daughter Ramtes	N	Length of Fruit [cm]	Width of Fruit [cm]
5	90	9.01 (±3.89)	13.67 (±5.24)	5.84 (±1.54)	5.35 (±1.35)	2.08 (±0.96)	65.67 (±34.29)	7.26 (±1.86)	90	1.17 (±0.18)	1.45 (±0.28)
6	63	5.10 (±1.41)	10.33 (±3.56)	5.72 (±1.14)	5.13 (±1.01)	1.33 (±0.62)	68.36 (±29.84)	8.70 (±2.23)	47	0.97 (±0.16)	1.15 (±0.19)
7	29	4.03 (±1.70)	4.40 (±1.68)	3.75 (±0.58)	3.52 (±0.49)	2.79 (±1.37)	23.51 (±14.31)	5.59 (±1.38)	5	0.86 (±0.21)	1.04 (±0.17)
8	80	4.81 (±1.71)	7.52 (±1.92)	5.38 (±1.13)	4.86 (±0.96)	2.28 (±1.18)	48.85 (±25.94)	7.54 (±2.29)	40	1.02 (±0.15)	1.29 (±0.24)
Kruskal–Wallis H test		288.89 *	297.70 *	214.71 *	200.25 *	115.54 *	135.70 *	83.02 *	-	82.82 *	89.66 *

3.4. The Effect of Environmental Factors on Coverage and Morphological Features of *P. indica*

The coverage of *P. indica* was significantly positively correlated with the Evenness index, the depth of the compacted soil layer, soil electrical conductivity, soil moisture, and the height of the herbaceous layer, while the number of species and the content of phosphorus in the soil showed an opposite effect (Table S7).

The Shannon-Wiener, Evenness, and Simpson indices had a significantly negative effect on some morphological traits, such as the number of stolons and the width of the fruit (Table S7). The number of species had a significantly negative influence on all morphological traits, except the number of daughter ramets. The light intensity also had a significantly negative effect on all morphological traits, except the number of stolons and size of the fruit. In contrast, the depth at which the compacted soil layer begins had a significantly positive effect on all morphological traits, except the size of the fruit. The soil electrical conductivity and moisture had a significantly positive effect on all morphological traits, except the number of stolons and the number of daughter ramets. The height of the herbaceous layer had a significantly positive effect on all morphological features, except the number of daughter ramets. There was no significant correlation between the soil pH, the content of nitrate, ammonium nitrogen, potassium, and phosphorus and the morphological traits of *P. indica* (Table S7). Moreover, the length of the pedicel and petiole, the length and width of the leaf blade, and the length of stolon were significantly positively affected by the coverage of *P. indica* (Table S7).

4. Discussion

P. indica shows a wide phytosociological spectrum, thriving in various plant communities, both in its native and secondary range. For instance, in Iran, in the westernmost part of its native range, it occurs in the deciduous forest communities *Parrotia persica-Carpinus betulus* and *Acer velutinum-Alnus subcordata-Carpinus betulus* [50], while in northern China, on the Guandi Mountain, it is a part of the secondary *Picea* forest [51]. Moreover, in Pakistan, in the Kashmir Himalayas, it is found as a dominant species of the community *Cynodon-Duchesnea-Zanthoxylum*, being common both in disturbed (eroded) and undisturbed (non-eroded) sites along roads [52]. In Europe, *P. indica* is usually treated as a species typical of nutrient-rich, mesic, and wet meadows and grasslands of the class *Molinio-Arrhenatheretea* [28,53]. However, nitrogen-rich and shady ruderal plant communities with a high share of *P. indica*, such as *Duchesneetum indicae* and *Oxalido-Duchesneetum indicae*,were also described from Europe [22,28]. Similarly, in this study, we evidenced a great phytocoenotic tolerance of *P. indica*, with the highest coverage in the ruderal community *Potentilla indica-Geum urbanum*, under semi-shade, moderate temperature, relatively low continentality, average moisture, slightly acidic, and nutrient-rich soil conditions. We assume that *P. indica* achieves different coverage in different plant communities not only due to environmental conditions but also depending on interspecific competition. In some study plots, *P. indica* suppressed *Agrostis capillaris*, *Geum urbanum*, *Poa trivialis, and Viola odorata*, while in others, it was dominated or outcompeted by expansive species such as *Aegopodium podagraria*, *Galeobdolon luteum*, *Lolium perenne*, *Rubus caesius,* and *Urtica dioica*.

Some authors [54] have proven that dense patches of *P*. *indica* can reduce the number of species and above-ground biomass of indigenous weeds commonly growing in the surroundings of crop fields in Japan, which may suggest a negative toxic effect of this species through allelopathy. Contrastingly, another study [55] showed a positive allelopathic effect of *P*. *indica* on the growth of lettuce (*Lactuca sativa*) seedlings. Nevertheless, competitive and allelopathic properties of *P*. *indica* in its secondary range require detailed studies.

Our results suggest that the presence and abundance of *P. indica* in urban habitats are strongly related to soil moisture, soil electrical conductivity, and soil fertility. In general, soil moisture and soil electrical conductivity are correlated with each other and the wetter the soil, the higher the soil electrical conductivity [56]. Nevertheless, soil moisture depends not only on the soil texture and porosity but also on many environmental factors such as climate, topography, and geology, as well as anthropogenic factors such as artificial irrigation and shading, which can be very diverse in urban areas [57,58]. In addition, urban soils can be highly heterogeneous in fertility and contamination [59]. According to Xuegang and Ming [30], the optimal habitat in which *P. indica* forms dense and extensive clusters has 80% of the maximum moisture content of the soil. Moreover, the clonal type of growth with physiological integration between maternal and daughter ramets allows *P. indica* to inhabit places with various degrees of salinity, including over-salinized ones with high soil electrical conductivity [21]. Given this, we confirmed that the coverage of *P*. *indica* increases with the soil moisture and soil electrical conductivity. In addition, the plots with *P. indica* were characterized by a higher content of nitrate and a lower content of ammonium nitrogen, potassium, and phosphorus. Also, the coverage of *P. indica* was negatively affected by the content of phosphorus. These results are consistent with the findings of Gray and Call [60], who proved that over-fertilization limits the occurrence of *P. indica* in tall fescue lawns. On the other hand, in nitrogen-rich environments, *P. indica* can be highly competitive due to the preferred investment in shoot biomass [26].

Although *P. indica* often occurs in trampled areas and its seeds can be spread by shoes along paths [28,29], we observed a low cover of this plant in sites exposed to human trampling (with compact soil and low herbaceous layer). This is not surprising since many authors have proven the negative impact of trampling on the plant cover [61]. Nevertheless, the low coverage of *P*. *indica* in some parks and roadsides in Kraków may result not only from human trampling but also from mowing, as pointed out by Gray and Call [60]. Interestingly, we revealed that the coverage of *P. indica* can be negatively affected by the number of species and positively by the Evenness index. This suggests that plant communities with higher species richness but dominated by one or a few native species are more resistant to *P. indica* invasion. The invasion-suppressing effect of native species diversity has been proven in other studies [62].

We documented significant differences in the quantitative morphological characteristics of *P. indica* between the groups of plant communities. Generally, *P. indica* is characterized by high phenotypic plasticity, which may give it an advantage in overcoming environmental stresses and may allow it to quickly adapt to local conditions [34]. Moreover, clonal integration possessed by *P. indica* is considered adaptive to various stressful factors such as high altitude [63], Pb contamination [64], and salinity [21]. According to Wang et al. [34], the plasticity of petiole length and old leaf chlorophyll content in response to light variation, as well as the plasticity of old and adult leaf chlorophyll content in response to nutrient variation, are of adaptive importance. Our results showing the negative effect of light intensity on petiole length and leaf blade size are consistent with the findings of Wang et al. [34]. Contrastingly, we did not find a positive correlation between light intensity and the number of ramets nor a significant effect of nutrient content on petiole length and leaf blade size, which may result from methodological differences. Notably, the length of the pedicels and stolons and the size of the leaves in *P. indica* increase with its coverage. Similar self-grown-reinforcing feedback was observed in *Solidago canadensis*, an invasive clonal plant with underground rhizomes [65]. Perhaps in larger and denser clones, the integration of ramets allows for the better use of environmental resources, or there is stronger support from the symbiotic microorganisms since the roots of *P*. *indica* are readily inhabited by various rhizosphere fungi [66]. Nevertheless, the biomass, number of ramets, and length of stolons in *P. indica* can be negatively affected by intraspecific competition, especially under low light intensity [67].

We further revealed that the species richness of the plant community reduces the values of morphological traits of *P. indica* (with no influence on the number of daughter ramets), while the height of the herbaceous layer has the opposite effect. This can be explained by interspecific competition for light, which is particularly strong in plant communities with high levels of nutrient availability [68]. In addition, morphologically, *P*. *indica* performs better on less compact soils, which confirms the known pattern of reducing the size of plants in places with high soil compaction [61]. Also, the positive effect of soil moisture and soil electrical conductivity on the morphological traits of *P. indica* is not surprising, as these two factors enhance its growth [21,30].

5. Conclusions

High spatial heterogeneity in plant cover, light intensity, and soil quality, usually occurring in urban areas may result in differences in the distribution, abundance, and morphological traits of *P. indica*. Nevertheless, the most important factors that may favor the spread of *P. indica* include high levels of soil moisture, soil electrical conductivity, and nitrate content, but high phosphorus content may inhibit the coverage of this species. As a clonal plant, in dense and extensive patches, *P. indica* increases the size of its leaves and flower stalks and the length of its stolons, which may allow it to effectively occupy space and compete with other species for light, especially in nitrogen-rich habitats such as riparian forests. To prevent the invasion of *P. indica* in riparian forests and other urban habitats, we recommend controlling its cultivation and disposal, removing new stands, and maintaining high species diversity with a dominance of one or a few native species in plant communities. When growing *P*. *indica* in botanical gardens, private gardens, or public urban greenery, it is important to prevent it from escaping into the wild. Excessively expanding plants should be removed together with stolons and daughter ramets. In addition, flowers and young fruits should be removed to prevent the dispersal of seeds by animals feeding on their fruits. We also recommend following the principles outlined in the European codes of conduct for invasive alien species in horticulture [69,70].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15122229/s1, Figure S1. Phytosociological relevé grouping by WPGMA method; Table S1. Characteristics of study sites; Table S2. Constancy degree and cover coefficient values of species in eight groups of phytosociological relevés with *Potentilla indica*. Acronyms of study sites are explained in Table S1; Table S3. Results of multiple comparisons between groups of phytosociological plots including number of species and Shannon-Wiener [H′] and Evenness [J′] indices. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with Bonferroni correction); ns—not significant; Table S4. Results of multiple comparisons between groups of phytosociological plots including Ellenberg's indicator values. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with Bonferroni correction); ns—not significant; Table S5. Results of multiple comparisons between groups of phytosociological plots including biotic and abiotic parameters. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with Bonferroni correction); ns—not significant; Table S6. Results of multiple comparisons between groups of phytosociological plots including morphological traits of *Potentilla indica*. The level of statistical significance: *—statistically significant differences between groups ($p < 0.0017$, H Kruskal–Wallis test with Bonferroni correction); ns—not significant; Table S7. Correlation between coverage and morphological features of *Potentilla indica* and environmental factors. The statistically significant values are bolded (* Pearson coefficient, ** Spearman coefficient).

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