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Distribution of the *Cannabis sativa* L. in the Western Himalayas: A tale of the ecological factors behind its continuous invasiveness

Sadia Jehangir[a,b], Shujaul Mulk Khan[a,c,*], Zeeshan Ahmad[d], Ujala Ejaz[a], Qurat Ul Ain[a], Linda Heejung Lho[e,**], Heesup Han[f,**], António Raposo[g]

[a] *Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan*
[b] *Department of Botany, Mirpur University of Science and Technology (MUST), Mirpur 10250, AJK, Pakistan*
[c] *Member, Pakistan Academy of Sciences, Islamabad, Pakistan*
[d] *CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla 666303, China*
[e] *College of Business Division of Tourism and Hotel Management, Cheongju University, 298 Daesung-ro, Cheongwon-gu, Cheongju-si, Chungcheongbuk-do 28503, the Republic of Korea*
[f] *College of Hospitality and Tourism Management, Sejong University, 98 Gunja-Dong, Gwanjin-Gu, Seoul 143-747 the Republic of Korea*
[g] *CBIOS (Research Center for Biosciences and Health Technologies), Universidade Lusófona de Humanidades e Tecnologias, Campo Grande 376, 1749-024 Lisboa, Portugal*

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ABSTRACT

The invasion of species in new regions depends on multiple factors, especially, the prevailing environmental factors. The environmental conditions are essential to understand for planning effective management strategies related to invasive species. Little is known about Cannabis as an established invasive weed. We hypothesized that the successful establishment of this invading species is influenced by the environmental variables; however, some of them have a much stronger influence than the others. Quantitative ecological methods were adopted for sampling the habitats invaded by *Cannabis sativa*, in a total of 165 quadrats. Soil samples were collected for soil analyses from each of those quadrat. Ecological and statistical approaches including Structure Equation Modeling (SEM) procedures were applied to evaluate the impact of environmental factors, ecological interrelationships, and the resultant invasiveness of the *C. sativa.* Our findings indicate that elevation, temperature, humidity, anthropogenic pressure, physio-chemical prperties of soil and habitat degradation play significant roles in determining the distribution and abundance of *C. sativa*. Principal Component Analysis (PCA) of the parameters further clarifies that elevation is the most important driver in explaining the successful establishment of the invader species with a 30.1% variance. Structural equation modeling further confirms the significant role played by elevation, which not only directly affects the abundance of Cannabis but also indirectly influences other variables such as anthropogenic pressure, temperature, and humidity etc. However, the invasion of *C. sativa* is less affected by soil saturation pH, electrical conductivity, phosphorous, potassium, and $CaCO_3$. Our study provides valuable scientific information that could be used for the early detection of invasive species at the early stage of invasion and in devising policies for their management and control.

* Corresponding author at: Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan.
** Corresponding authors.
E-mail addresses: smkhan@qau.edu.pk (S.M. Khan), heeelho@gmail.com (L.H. Lho), heesup.han@gmail.com (H. Han).

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1. Introduction

Cannabis sativa L., is one of the earliest domesticated plant species over 10,000 years (Hussain et al., 2021). The cultivation history of *Cannabis* plant is long (Russo, 2007), which started when nearby naturally occurring stands were depleted due to early human settlements and expansion. The earliest farmers began to grow cannabis plants close to their settlements (Clarke and Merlin, 2016). The selection of plants with better desired products started as a part of their ancient agricultural practice during this domestication period. Economic traits like edible seeds, strong fiber, and psychoactive resin were readily noticed and encouraged. Humans became more and more selective as their familiarity with cannabis and its products increased. The selection of cannabis for different economic traits continued along with its spread beyond its native range (Clarke and Merlin, 2016). However, cannabis origins have been attributed to a broader region that is referred to as central Asia, which is presently China (Schultes, 1969; Merlin, 1972). Cannabis expanded its range beyond the center of its origin eastward toward Northeastern China and the west, headed to Eastern Europe (McPartland, 2018; McPartland et al., 2019), and it continues to disperse to other regions of the world.

The dispersal of cannabis beyond Eurasia occurred in relatively recent history which was subdivided into six phases (Clarke and Merlin, 2013). Phase I is the primary dispersal phase across Eurasia, was about 10,000–2000 years BP (before present), phase II evident spread into Africa and Southeast Asia about 2000–500 years BP, and phase III witnessed expansion from Europe into the Americas in 1545–1800 CE (common era), phase IV received diffusion from Asia and Europe into the Americas in 1800–1945, phase V is the further expansion after World War II in 1945–1990, and phase VI is the proliferation of cannabis mainly industrial hemp from 1990 CE to present. More than 135 countries and territories document the most recent record of the occurrence of the cannabis plant, and it was declared invasive in 50 of these countries (Canavan et al., 2022). Further, its distribution is likely underreported because it is estimated that cultivation, which occurs at different levels, is happening in 172 countries as an illegal drug.

The invasion potential of different plant species is greatly influenced by their domestication (Molina-Montenegro et al., 2014; Iram et al., 2020). Species under high intensity management, such as food crops have lower invasion risk while the species under low intensity management have high invasion risk e.g., biomass producing crops (O'Neill et al., 2021; Zhao et al., 2023). Both scenarios are true for cannabis based on its intended wide array of usage. Studies on the invasiveness of invasive species reveal there are certain species with specific characteristics that contribute to their invasion ability (Van Kleunen et al., 2010; Davidson et al., 2011). Species specific characteristics that are believed to contribute to invasiveness include life history, competitive ability, genetic variation, hybridization, phenotypic plasticity, dispersal capability, tolerance to a wide range of environmental conditions, resistance and allelopathic effect (Davidson et al., 2011; Tabassum and Leishman, 2018; Ullah et al., 2022; Cranberg and Keller, 2023). Cannabis possesses various aforementioned species specific traits that contribute to its invasive capability such as high competitive ability, rapid growth, annual life form and photosynthetic efficiency (Guo et al., 2018). In wild habitats, cannabis develops a dense thicket population reducing the availability of light that may have a detrimental impact on the emerging seedling of native plants (McPartland, 1997; Small et al., 2003; Noreen et al., 2019; Haq et al., 2020).

It shows a high tendency to hybridize due to historical movements (intentional or unintentional) and cross-fertilization through wind-born pollens. The cannabis plant reproductive system is characterized by anemophily and allogamy. Hence, open pollination is necessarily responsible for a certain degree of hybridization between wild and improved populations (Barcaccia et al., 2020; Canavan et al., 2022). However, the viability of pollen declines linearly with increasing distance but in the case of cannabis, hybridization has been observed over a substantial distance of 100 km. This hybridization tendency greatly assisted isolated populations in overcoming and crossing biogeographic barriers (Rahn et al., 2016; Campbell et al., 2019). Further, seeds of cannabis have the capability to escape and spread to a considerable distance from their cultivation point. There are two main dispersal pathways for Cannabis seeds one is water and the other is endozoochory. Cannabis seeds were discovered to be more buoyant when compared to (93 species) other invasive species (Moravcova et al., 2010), which allowed them to float and be carried by rivers. The seeds can also be spread over great distances since they are edible to animals and can survive in their excreta (Campbell et al., 2019). These dispersal mechanisms and viability of seeds (McPartland and Naraine, 2019) significantly contribute to their widespread distribution and capability to establish in a variety of habitats. At the same time, worldwide occurrence records of cannabis (feral/wild) from every habitable continent evident for its ability to tolerate a broad environmental gradient. This broad tolerance breadth may be shaped by several contributing factors such as early dispersal by humans, clandestine breeding and tendency of cultivated plants to escape and hybridize across larger geographic range (Canavan et al., 2022).

Species specific characteristics are essential for its invasiveness. The success of any species in a new range to become invasive is primarily influenced by the environmental characteristics broadly categorized into biotic and abiotic factors. Any successful invader must generally get through the abiotic filter, representing chemical and physical characteristics in the receiving environment. The concept of abiotic filtering emphasizes the interplay among living organisms and their surrounding environment, recognizing that every organism could not possibly thrive and establish in the prevailing abiotic conditions (Kraft et al., 2015). Understanding the abiotic filter provides information related to invasion success and establishment.

Evaluation of abiotic environmental conditions that significantly influence its success becomes a task of interest for invasion biologists and environmental managers by considering the economic, ecological, and social importance of widely distributed cannabis. Therefore, we have hypothesized that the successful establishment of invading species is influenced by the environmental variables, whereas some of the variables have much stronger influence than others. In the case of *Cannabis sativa* species, the anthropogenic activities and habitat alteration interfere with the prevailing conditions and likely lead to enhanced invasion. This research article aims to 1) assess the abundance of *Cannabis sativa* along the elevation gradient of varying ecological habitats, 2) assess the environmental variables and their relationship 3) modelling the habitat degradation, anthropogenic pressure and natural drivers in relation to cannabis invasion.

2. Materials and methods

2.1. Description of study site

The state of Azad Jammu and Kashmir (AJK) geographically lies between 33° – 36° latitude north and 73° – 75° east longitude (Iqbal and Khan, 2014; Shaheen et al., 2015). It falls in the Western Himalayan orogen belt (Shaheen et al., 2015), and it comprises ten districts that are broadly divided into the southern districts and the northern districts (Fig. 1). The southern districts (Bhimber, Mirpur, and Kotli) are relatively plain in contrast to the northern districts (Poonch, Bagh, Muzaffarabad, Haveli, Hattian, Sudhnoti, and Neelum) that have remarkable mountainous peaks (DD, 2017). The elevation greatly varies across the study area, which ranges from 360 m in the south to the peaks of 6325 m in the northern parts. The climatic conditions of the area vary accordingly with the south having dry sub-tropical to moist temperate climatic conditions in the north (Abdullah et al., 2021; Iqbal et al., 2021). The minimum average temperature in the winter ranges from 4 ℃ to 7℃, whereas the maximum average temperature in the summer ranges from 20℃ to 36℃. The maximum temperature reaches 45℃ in the months from May to September in the southern parts. The average annual rainfall ranges between 1000 mm and 2000 mm. The study area presents different climatic conditions, habitats, and soil types (Khan et al., 2012; Amjad and Arshad, 2014). The diverse climatic conditions and topography of the study area make it suitable to support and harbor diverse flora performing a range of ecosystem services. However, this rich diversity is at a greater risk imposed by invasive species which can replace the native flora once they successfully establish their communities.

2.2. Vegetation sampling

The current distribution of cannabis in the study area was recorded during the field trips conducted from April to August during

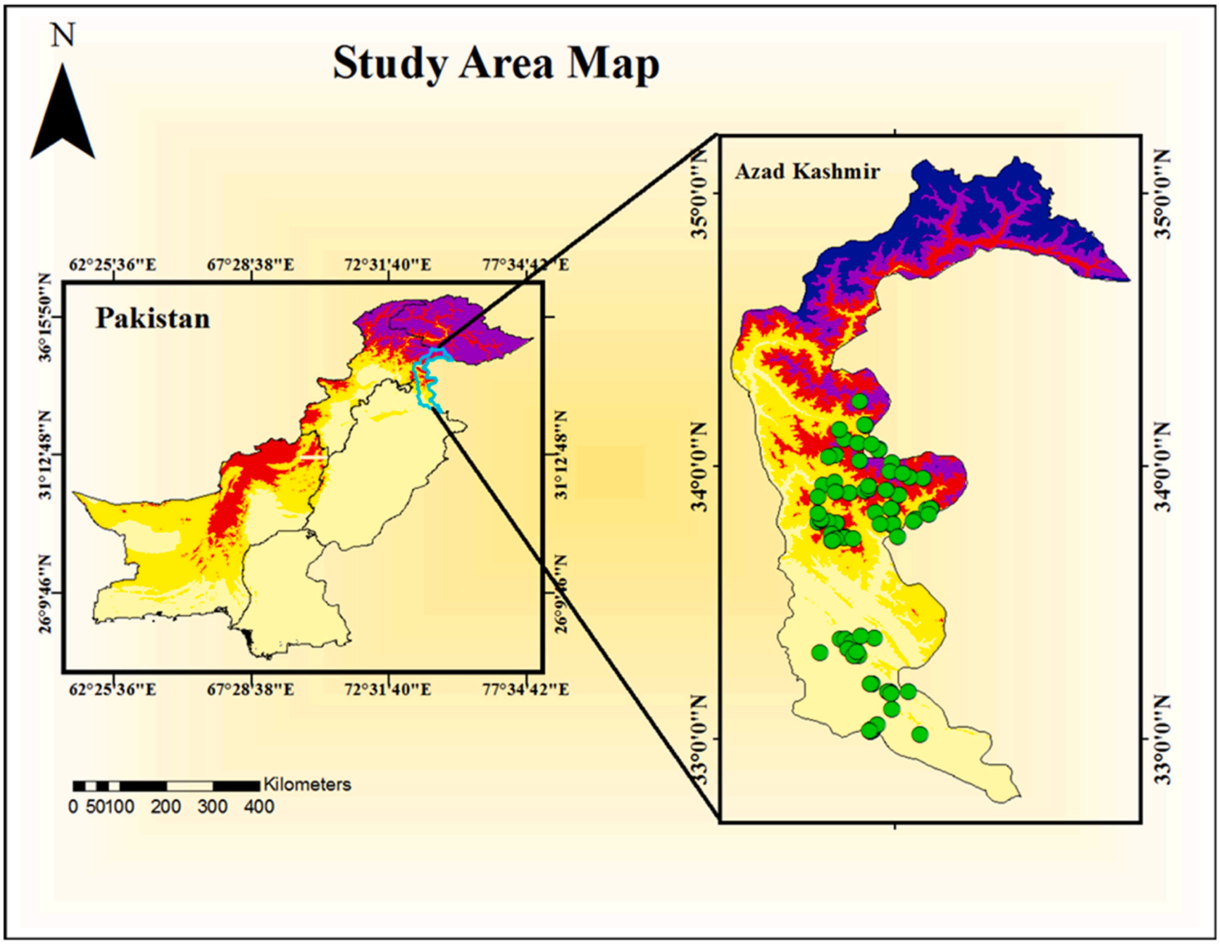

Fig. 1. Map of the study area (Kashmir, Pakistan) with green colored dots representing the sampling sites for *Cannabis sativa* established and associated communities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

years 2021–2022. A total of six stations were established using a partially randomized approach for the vegetation sampling of the invaded communities dominated by cannabis. In these communities, cannabis was already established where its occurrence dates back to 1832 (Fig. 2) (https://www.tropicos.org/Project/Pakistan, Joseph et al., 2011, Kisielowska et al., 2012). It was used as a stable drug in study area in the 1950–1970s (Hussain et al., 2022). A varied number of quadrats depending on the geography, elevation, microclimatic conditions, and vegetation structure were placed at each station. The altitudinal range of the study area varies from 239 to 2226 m. In total 165 rectangular quadrats of 1 m × 1 m size were established. The primary phytosociological attributes, such as density, cover, and frequency were recorded at each quadrat by following the standard method (Cox, 1972; Mueller-Dombois and Ellenberg, 1974; Khan et al., 2013b; Bano et al., 2018; Anwar et al., 2019, 2023). The geographic attributes, such as elevation, latitude, and longitude were recorded as well at each quadrat by using a Global Positioning System (GPS) (Khan et al., 2014; Ahmad et al., 2016; Iqbal et al., 2017). Furthermore, the cover of bare land in the total cover was also noted in order to assess its relationship with the invasion.

2.3. Environmental variables

Environmental variables, such as humidity and temperature were recorded at each quadrat by using a hygrometer during fieldwork (ThermoProTP50). The soil samples were also collected from each quadrat up to a depth of 15 cm, and they were placed in polythene zipper bags (Iqbal et al., 2021; Zeb et al., 2021). The soil samples were dried at 105 ℃ for the chemical assay. The dried soil was sieved and ground in order to form a homogenous mixture. Distilled water (50 ml) was added to the soil sample, and it was then placed on a magnetic stirrer in order to ensure a homogenous solution. The electrodes of the electrical conductivity (EC) and pH meter were immersed in soil suspension, and their respective values were recorded (Koehler et al., 1984; Ahmad et al., 2016; Khan et al., 2022; Rasheed et al., 2022). The available phosphorus (P) content was determined by following the method by (Kitayama and Aiba, 2002), while available potassium (K) and calcium carbonate ($CaCO_3$) were measured using standard protocols by (Loeppert and Suarez, 1996; Shafiur Rahman et al., 2016). The content of organic matter was determined according to (Jackson, 1962; Hussain et al., 1999).

2.4. Anthropogenic pressure

The influence of anthropogenic activities and habitat degradation were estimated visually in each quadrat. The different classes for anthropogenic pressure were structured based on the level of intensities, which were measured using a 4-point scale, where 3 was used for a higher level of anthropogenic pressure, 2 for a moderate level, 1 for a low level, and 0 for the absence of anthropogenic pressure (Manan et al., 2020). The quality of the habitat was observed and structured into four classes by using the same 4-point scale, which included 3 for high, 2 for moderate, 1 for low, and 0 for the absence of habitat degradation.

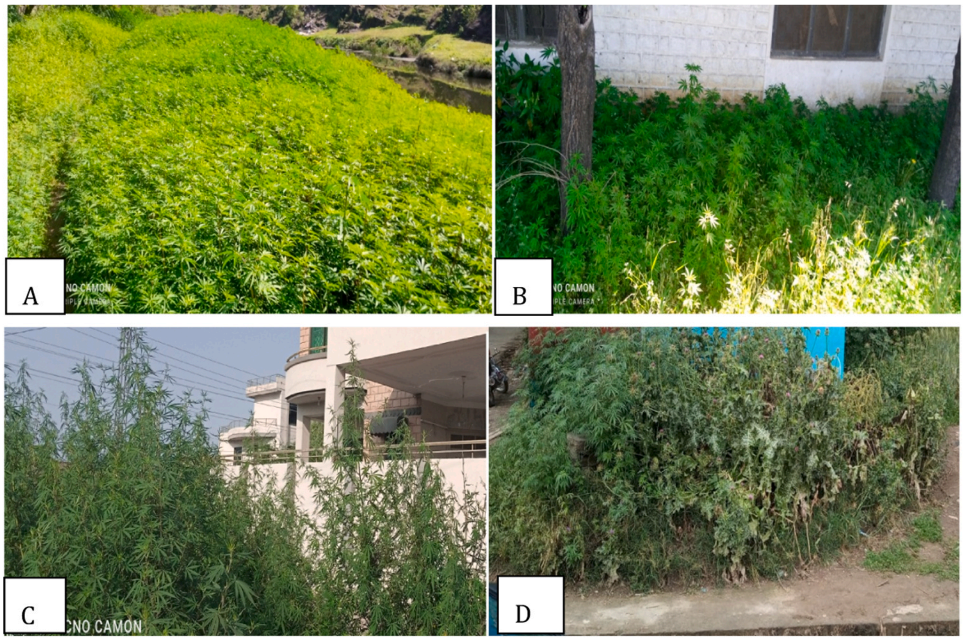

Fig. 2. *Cannabis sativa* invasion in different habitats. A)along water body, B) degraded habitat, C) abandoned land, and D) the edge of a crop field:- in association with other invasive species.

2.5. Statistical data analyses

The data was analyzed, using a multivariate statistical analyses in order to assess the factors behind the successful establishment and invasiveness of cannabis in different habitats.

2.5.1. Linear regression analyses

A linear regression analysis is a statistical approach that is used in order to assess the relationship between the explanatory and response variables (Ali et al., 2022, 2023b). We used linear regression analysis to assess the impact of different explanatory variables (environmental factors) in determining the distribution and abundance of cannabis in invaded communities. The equation for linear regression is provided below.

$$Y = a + bX$$

Where **Y** represents the response variable, **X** represents the explanatory variable, **a** denotes the intercept, and **b** is the slope of the line. Linear regression calculates the explanatory variable value from the response variable.

2.5.2. Pearson's correlation

Pearson's correlation matrix was used to investigate how multiple variables are associated with each other (Ali et al., 2023a). We used Pearson correlation to assess the relationship of environmental variables with plant abundance of cannabis and all the variables with each other. Pearson's correlation coefficient was estimated by using the formula that is provided below.

$$\boldsymbol{r} = \frac{\sum_{\mathbf{i}}(\mathbf{x_i} - \mathbf{x}^-)((\mathbf{y_i} - \mathbf{y}^-)}{\sqrt{(\mathbf{x_i} - \mathbf{x}^-)2}\sqrt{(\mathbf{y_i} - \mathbf{y}^-)2}}$$

Where $\boldsymbol{r}$ corresponds to the Pearson's correlation coefficient, $\boldsymbol{x_i}$ represents the total observation, $\boldsymbol{x}^-$ shows the mean of a specific variable, $\boldsymbol{y_i}$ represents the total observation, and $\boldsymbol{y}^-$ is the mean of a specific variable (Ahmad et al., 2021). It tells the strength of the correlation among the different variables, which occur between − 1 and + 1. The positive and negative integers denote the direct and inverse relation between the variables. The closer the integer's number is to either − 1 or + 1, the stronger the relation, whereas there is the absence of any relation if the coefficient value is 0.

2.5.3. Principal component analysis (PCA) of the parameters

A principal component analysis (PCA) applied on a large data set reduces dimensionality and increases interpretability as well as maintains its original structure to a maximum extent (Chu et al., 2018). The PCA of the parameters was applied in order to assess the variance posed by different explanatory variables. The arrows correspond to the explanatory variable, and their lengths symbolize the magnitude of the strength. If any of the two arrows have a 90º degree angle, it indicates the absence of any relation among variables. Negative relation if it makes a 180º angle, while positive relation if parallel to each other.

2.5.4. Structure equation modeling

The Structural Equation Model (SEM) was designed to test our hypothesis by using R software Version 4.2.2 (Team, 2013). It is a combination of multiple regression and factor analysis. Maximum likelihood was used for coefficient estimation along with scaled statistics and standard error. The residuals and modification indices were used for the inclusion and exclusion of the measured variables. The goodness of the model fit was assessed through Chi-square, Adjusted Goodness of Model Fit Index (AGFI), Goodness of Model Fit Index (GFI), Comparative Fit Index (CFI), Root Mean Square Residual (RMR), Normed Fit Index (NFI), Akaike Information Criterion (AIC) and Standard Root Mean Square Residual (SRMR) (Ahmad et al., 2022, 2023).

3. Results

The abundance of *Cannabis sativa* varies greatly in the Western Himalayas, reaching a maximum abundance (Importance value index (IVI) = 151.0) in the southern parts, in contrast to the northern parts with a minimum abundance (IVI = 01). The elevation, temperature, humidity, and saturation attain a great variation and it builds up a wide environmental gradient, which is shown in descriptive statistics Supplementary Table 1. The soil of the Western Himalayas is acidic through natural to alkaline with a pH range of 6.2–8.2. The soil characteristics, such as E.C, P, K, and $CaCO_3$ attain more variations compared to the OM. Moreover, anthropogenic pressure and habitat degradation variation are interlinked, which establish the same range. The bare land differs greatly across different habitats (Supplementary Table 1).

We also recorded a total of 77 associated plant species belong to 27 different families during our study. Poaceae family was identified as the dominant family (23%), which surpassed Asteraceae (20%), followed by Lamiaceae and Fabaceae (5.9%). The rest of the families contained only a few species (Supplementary Table 1). *Cannabis sativa* was the most dominant invasive plant species followed by *Parthenium hysterophorus*, *Cynodon dactylon*, *Silybum marianum* and *Centaurea iberica* based on the importance value index (Supplementary Table 2).

3.1. Influence of environmental variables

The linear regression was used in order to assess the impact of the environmental variables on the abundance of cannabis that drives its successful establishment. Cannabis declines linearly with increasing elevation, which poses a highly significant impact on its

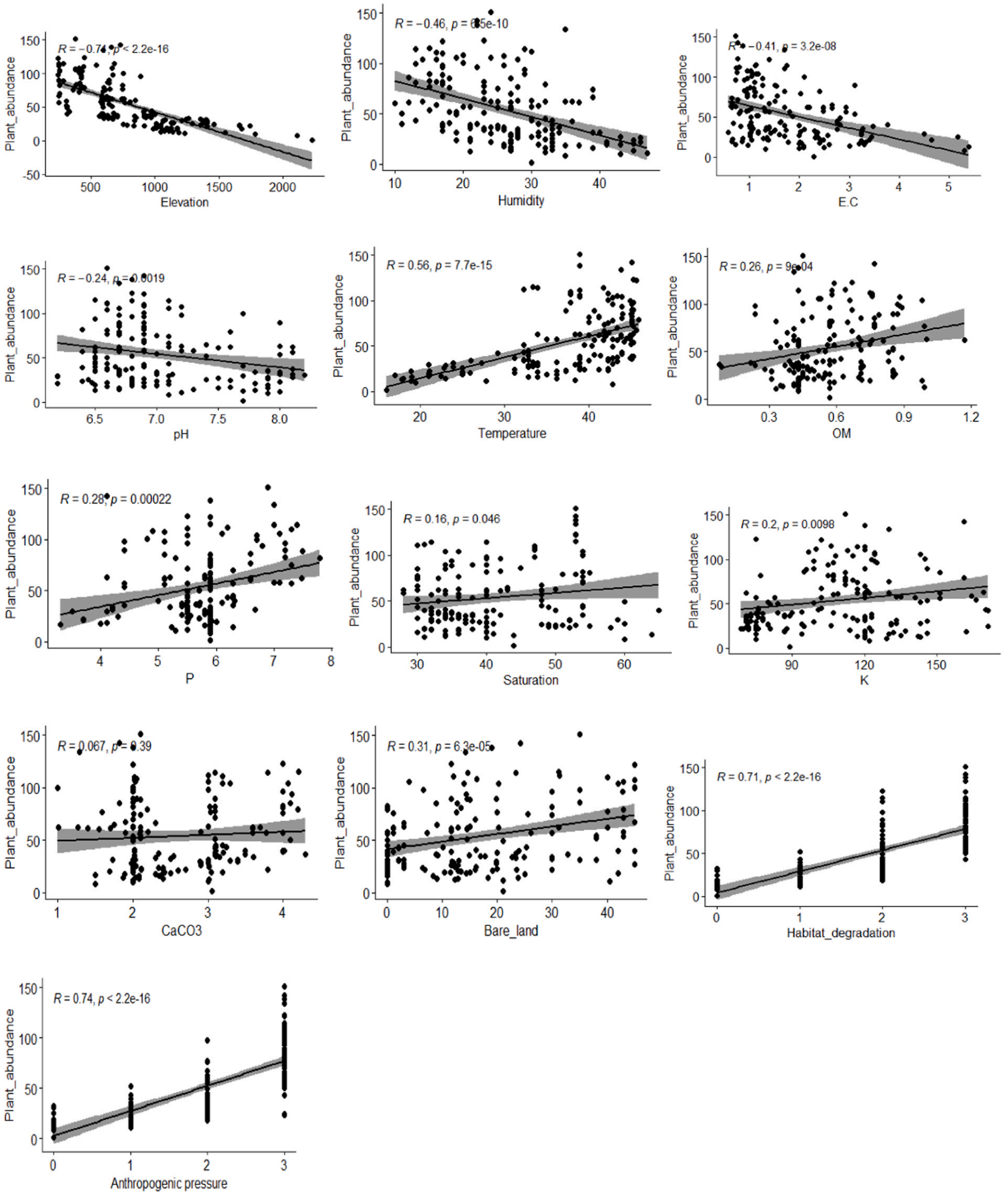

Fig. 3. The relationship between *Cannabis sativa* abundance and several environmental factors using linear regression analysis; Elevation, Humidity, Electrical conductivity (EC), pH, Temperature, Organic matter (OM), Phosphorus (P), Saturation, Potassium (K), CaCO3, Bareland, Habitat degradation, Anthropogenic pressure.

abundance (R= −0.71 and $p = 0.00022$). The plant abundance attains its maximum value in an altitudinal range of 239–750 m, which swiftly declines after 1500 m due to its strongly negative impact. Cannabis abundance tends to increase significantly with the temperature (R= 0.56 and $p = 0.0007$), as shown in Fig. 3. Temperature positively influences the plant abundance, which becomes maximum in a range of 32–43 °C. The minimum abundance was observed below 20 °C in the northern parts of the Western Himalayas. Humidity has a statistically significant and weak negative impact on cannabis abundance (R= −0.46 and p = 0.00065). The maximum abundance is observed between 20% and 30% humidity levels. Soil saturation, organic matter, P, K, and $CaCO_3$ have a very weak and positive impact, while pHhas a weak negative effect. Anthropogenic pressure (R=0.74 and $p = 0.00022$) and habitat degradations (R=0.74 and $p = 0.00022$) have a strongly positive and significant impact on cannabis abundance. Cannabis abundance reached its maximum at a high level of both anthropogenic pressure and habitat degradation. The proportion of bare land in each quadrat has a positively weak influence on the cannabis abundance (R= 0.31 and $p = 0.0006$), which clearly states that the bare land condition aids in regards to establishing the cannabis abundance, which is shown in Fig. 3.

3.2. Correlation among the environmental variables

Cannabis abundance has an indirect relation with elevation. The correlation value (−0.71) divulges a strong association in response to which the abundance declines with an increasing elevation, which is shown in Fig. 4. Temperature (0.56) was found to be positively correlated with cannabis abundance. This is in contrast to humidity, which establishes a negative correlation. Moreover, anthropogenic pressure (0.74) and habitat degradation (0.71) were found important variables in regard to explaining the cannabis abundance. Both the variables have a strong positive correlation. The abundance is not only directly affected by environmental variables but also indirectly due to their existing affinity with each other. For instance, elevation negatively influences temperature and anthropogenic pressure which in turn affects abundance. Similarly, humidity increases with elevation, which is due to their positive correlation, but it decreases with temperature. The content of organic matter, soil saturation, P, K, $CaCO_3$, pH E.C, and bare land were found to be less important in regards to explaining the cannabis abundance, which is shown in Fig. 4.

3.3. Variance among the influence of environmental variables

The Principal Component Analysis (PCA) of the parameters was used to assess the variance imposed by different variables on cannabis abundance. In general, 62% of the variance was explained by the first four principal components (PCs). Elevation contributed 30.1% of the total variance, so it was declared as the most important environmental variable in determining the successful establishment of cannabis. Anthropogenic pressure contributed 13.6%, while habitat disturbance contributed 10.6% of the total variance as shown in Fig. 5. Temperature explains 9% of the variance, whereas humidity contributed 7.8% of the variance. The soil variables are

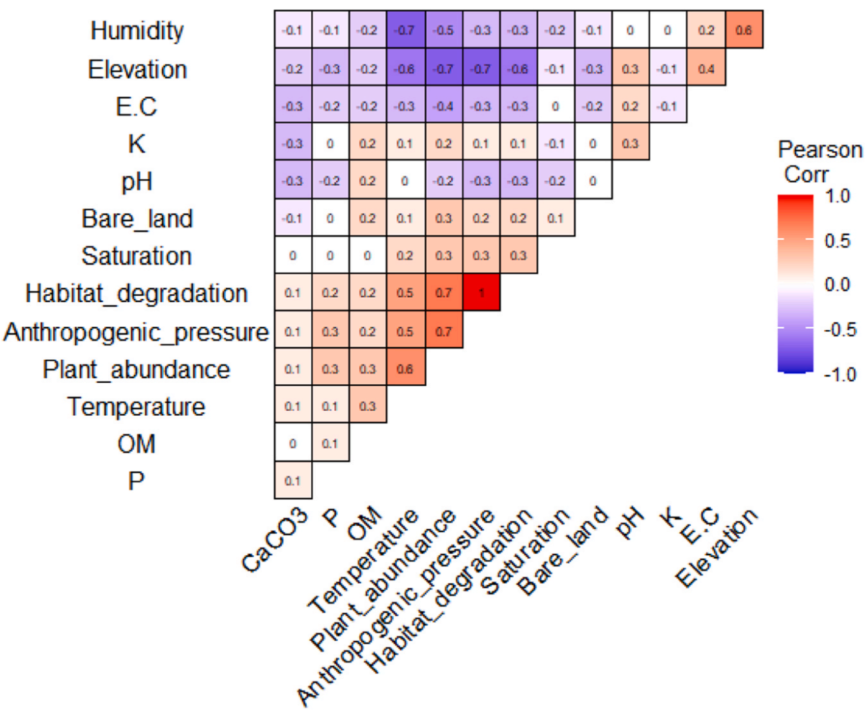

Fig. 4. Pearson's correlation matrix of *Cannabis sativa,* showing the strength of correlation among the environmental variables. E.C (electrical conductivity); K (potassium); OM (organic matter); P (phosphorus).

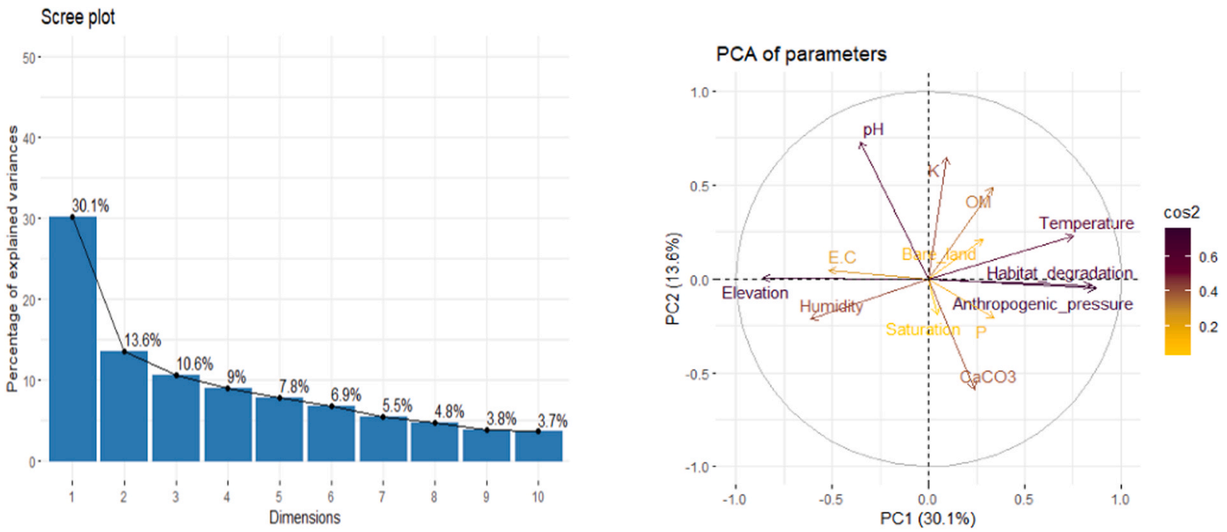

Fig. 5. Principal component analysis of parameter for ecological factors. PCA of parameter (right side) arrows length shows variance among PCs and scree plot (left side) gives variance in percentage among PCs. E.C (electrical conductivity); K (potassium); OM (organic matter); P (phosphorus).

important in explaining the abundance, but they have comparatively low variance. Soil pH has 6.9% of the variance, which is followed by E.C with 5.5%, and organic matter with 4.8%. Phosphorus contributed 3.8% of the variance, and K contributed 3.9% which illustrates their equal importance. Soil saturation, $CaCO_3$, and bare land contributed the least to the total variance, which is shown in Fig. 5 and Supplementary Table 3. PCA of parameters results clearly illustrate that all the measured variables differ from each other in terms of the variance they imposed to affect the plant abundance of cannabis in the invaded communities.

3.4. Impact assessment of the environmental variables through Structural Equation Model (SEM)

The structural equation model was designed to further evaluate our hypothesis. Elevation has a direct, negative, and significant impact on the abundance of cannabis ($\beta = -0.33$) that declines with increasing elevation (Table 1; Fig. 6). Anthropogenic pressure significantly increases cannabis abundance ($\beta = 0.51$) as both have a positive and direct relation with each other. Temperature and habitat degradation have a direct effect while humidity has an inverse effect on cannabis abundance and hence establishment (Table 1; Fig. 6). Model fit indices values such as Chi-square, p-value, AGFI, NFI, GFI, CFI, SRMR, RMR and AIC lie in the range of goodness of fit and comprehend the model fitness as shown in Table 2.

We have also checked both the direct and indirect effects of all the measured variables on the cannabis abundance (Supplementary Table 4). Elevation influence on plant abundance is not only direct but also indirect where it negatively influences with high significance ($p < 0.0001$) through mediators such as temperature ($\beta = -0.62$) and anthropogenic pressure ($\beta = -0.65$). Although elevation and humidity have a direct relation with each other, but humidity has a negative and insignificant effect on cannabis abundance. The total effect of all the measured variables of both direct and indirect paths is significant as shown in Supplementary Table 4.

Table 1
Detailed summary of SEM of cannabis abundance in relation to elevation, humidity, temperature, anthropogenic pressure and habitat degradation on plant abundance of cannabis.

Response	Predictor	Estimate	S.E	Z- value	*p*-value
Plant abundance	Elevation	-0.329	0.074	-4.421	0.0001
Plant abundance	Temperature	0.033	0.07	-3.471	0.053
Plant abundance	Humidity	-0.09	0.065	-1.385	0.166
Plant abundance	Anthropogenic pressure	0.505	0.196	2.582	0.010
Plant abundance	Habitat degradation	0.23	0.191	-2.255	0.057
Temperature	Elevation	-0.62	0.061	-10.157	0.001
Humidity	Elevation	0.33	0.083	3.965	0.001
Anthropogenic pressure	Elevation	-0.654	0.059	-11.095	0.0001
Habitat degradation	Elevation	0.011	0.025	0.43	0.667
Humidity	Temperature	-0.57	0.07	-8.108	0.0001
Humidity	Habitat degradation	0.208	0.071	2.933	0.003
Habitat degradation	Anthropogenic pressure	0.977	0.025	39.033	0.0001

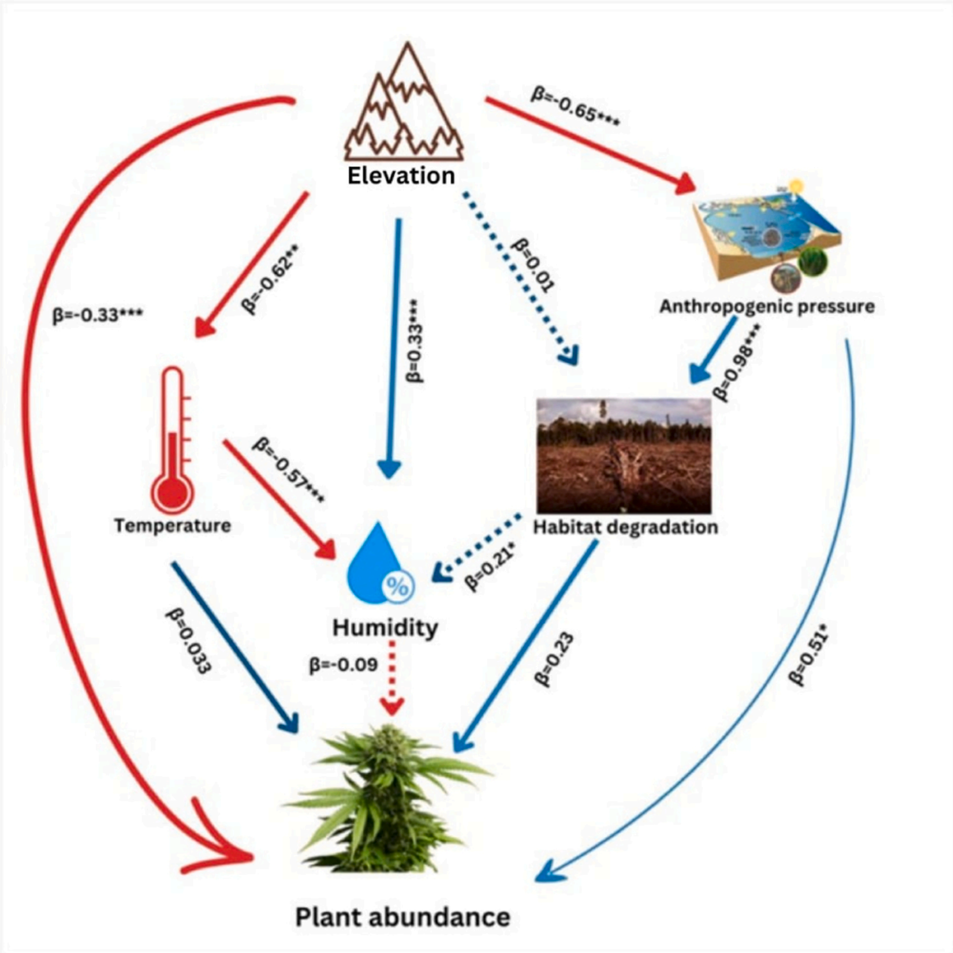

Fig. 6. Structural equation modeldemonstrating direct and indirect structural relation of *Cannabis sativa* abundance in response to measured variables. Note: The blue solid lines symbolize significant and positive relationships while the red solid line symbolizes negative and significant relationships. Dotted blue and dotted red lines comprehend insignificant positive and negative relationships respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of model fitness showing different model fit indices.

Chisq	*p*-value	NFI	CFI	GFI	AGFI	SRMR	RMR	AIC
11.003	0.112	0.988	0.991	0.984	0.987	0.055	0.055	1446.181

4. Discussion

The potential of invasive species to colonize and establish in a new habitat generally depends on their ability to tolerate abiotic conditions (Alpert et al., 2000; Levine et al., 2004), biotic resistance (Bogdziewicz et al., 2019), and propagule pressure (Lockwood et al., 2005; Simberloff, 2009a), or a combination of all these factors. The present study aims to identify drivers for the successful invasion of cannabis in the wild habitat of the Western Himalayas. The present study recorded 78 plant species from invaded cannabis communities of 28 different families. The species composition is similar to those reported from the Himalayas (Khan et al., 2016; Rahman et al., 2020; ul Haq et al., 2020; Anjum et al., 2022; Jamil et al., 2022; Manan et al., 2022). Poaceae and Asteraceae were the leading families that comprised most of the reported species, and they are in agreement with (Shaheen et al., 2011; Ilyas et al., 2013; Abbas et al., 2016; Amjad et al., 2017; Jamil et al., 2022).

Environmental variables are important in regards to explaining the abundance of cannabis as it significantly declines along the elevation. Our study is consistent with the other studies that suggested that invasive species richness and abundance decline along with elevation (Pauchard and Alaback, 2004; McDougall et al., 2005; Kalwij et al., 2008; ur Rahman et al., 2021). This significant decline in the abundance of cannabis along the elevation is in close approximation with the studies by (Alexander et al., 2011a) and (Seipel et al., 2012), which advocate directional filtration (Alexander et al., 2011a; Averett et al., 2016). The distribution pattern of invasive species along the altitudinal gradient is driven by climatic constraints and human influences. Another possible reason might be that all the alien species are not pre-adapted to the survival conditions at higher elevations that aid to pass through environmental constrains and are unable to survive, so they fail to colonize. However, only broad ecological amplitude species pose climatic tolerance capability and grow in a wide range of climatic conditions and eventually reach higher elevations (Becker et al., 2005; Alexander et al., 2011b; Marini et al., 2013).

Temperature is another influential factor that plays a highly significant role in the distribution and abundance of cannabis. Our findings are consistent with the study by (WERF et al., 1995), that the rate of leaf appearance and stem elongation linearly increases with temperature in a range of 10 ℃ to 28 ℃. The optimum temperature for the photosynthesis of cannabis occurs in the range of 25 ℃ to 30 ℃, whereas the maximum transpiration is at 40 ℃. The optimum temperature for the maximum seed germination ranges between 19 ℃ to 30 ℃, whereas the maximum temperature for seed germination was 40 ℃ (Geneve et al., 2022). The optimum temperature of the plant species mirrors its physiological and genetic adaptation toward the environmental temperature range (Berry and Bjorkman, 1980). This greater variation in the temperature range could be explained by the high degree of plasticity exhibited by the plants in response to temperature based photosynthesis.

Our findings of declines in the abundance of cannabis with humidity contradict the previous findings that the required humidity level is 75% for the development stage, 55–65% in the vegetative and flowering stage (Chandra et al., 2017), and as high as 90% in the propagation stage (Hawley, 2018; Magagnini et al., 2018). The disagreement of our findings with the previous studies could be attributed to the fact that relative humidity is measured at different stages of the life cycle under control conditions. However, our study is regardless of any particular stage of the life cycle as well as the control conditions. Furthermore, the altitudinal gradient, which is seen in our study, changes the microclimatic conditions, such as humidity, temperature, and precipitation (Vittoz et al., 2010; Zhang and Shao, 2015), which could attribute to distinct vegetation (Champion et al., 1965; Khan et al., 2011, 2013a; Nasrullah et al., 2015) and differs greatly from the experimental setup under controlled conditions.

The soil's pHis one of the major underlying abiotic variables that has a complex effect on plant growth, and it leads toward the variation in the distribution of the plant species in calcareous or acidic soils, which determines the floristic variation in different communities (Diekmann and Lawesson., 1999; Simberloff, 2009a,b). However, pH appears to have a trivial effect on the abundance of cannabis in the current study. The suitable pH for its growth ranges between 6.0 and 7.5 (Amaducci et al., 2015), whereas an optimum pH occurs in the range of 5.8–6.0 (Bocsa and Karus, 1998). Several weeds possess excellent ability to grow across a wide range of pH such as *Campsis radicans* Seem (Chachalis and Reddy, 2000), *Eleusine indica* (L.) Gaertn (Chauhan and Johnson, 2008), *Solanum rostratum* Dunal (Wei et al., 2009), and *Urena lobata* L. (Wang et al., 2009), and they are comparable with our findings that pH is not a limiting factor for their distribution and abundance.

Soil saturation and Cannabis abundance were found to be positively correlated. Our results are consistent with (AJ and CA, 1947). They suggested that cannabis grows well in high water holding soils and shows sensitivity toward droughts. Cannabis requires a high moisture content right through its growing season, particularly during their establishment stage in the first six weeks of growth (Dewey, 1913; Ozturk et al., 2022). The plant can endure drier conditions once the plant becomes well rooted because their roots have the capacity to penetrate 2–3cmin depth in order to extract moisture (Amaducci et al., 2002).

Soil organic matter, available P and K, shows a positive and weak correlation with cannabis. The weak positive correlation of cannabis with P and K and organic matter might be due to low concentrations and the low availability of these nutrients in wild habitats. Our findings corroborate with Caplan et al., (2017), Khan et al. (2023). They reported that organic fertilizers improve plant growth at their vegetative stage. The findings by Vera et al. (2004) are in agreement with our findings that P increases plant height, even though its effect on the total biomass and the seed yields were minimal and inconsistent. The study by Finnan and Burke (2013) also reported that P had a negligible impact on the stem yield. Furthermore, our results of K's negligible positive effect are comparable with Cockson et al. (2019), which included that K did not significantly affect the total biomass and the seed yield of hemp plants.

Anthropogenic activities have a significant impact on the abundance of cannabis. Our findings support the previous studies by Van Der WAL et al. (2008b), Catford et al. (2009), Pauchard et al. (2009), Pollnac et al. (2012). Our findings are further supported by the study by Fuentes-Lillo et al. (2021), who reported that the invasive species abundance and richness are derived from anthropogenic factors both at the local and regional scales. The mountains in different regions also witnessed anthropogenic factors as one of the most important invasion drivers, which included Ecuador (Sandoya et al., 2017), Yellowstone National Park (Pollnac et al., 2012), Bolivia (Fernández-Murillo et al., 2015), and Norway (Lembrechts et al., 2017; Clavel et al., 2021). The increases in the success rate of invasion due to the anthropogenic factor might be explained by the fact that it acts as a vector for the propagules transportation on one hand, whereas it modifies the prevailing abiotic and biotic conditions on the other, which therefore increases the possibility of their successful establishment in new habitats (Van Der WAL et al., 2008a; Catford et al., 2009; Pauchard et al., 2009; Pollnac et al., 2012; Cabra-Rivas et al., 2016; Lembrechts et al., 2017).

Habitat degradation and invasion are interrelated (Marvier et al., 2004; Didham et al., 2007; Ewers and Didham, 2007; Foxcroft et al., 2011b)which significantly increases the cannabis abundance in Western Himalaya. Our findings are consistent with other studies, such as (Vilà et al., 2007; Thiele et al., 2008; Dawson et al., 2015). The habitat disturbance hypothesis supports our findings that habitat alternation or degradation favors the establishment of invasive species (Hobbs and Huenneke, 1992; Richardson and Pyšek, 2007) by modifying both the abiotic and biotic conditions, which cause the habitat to become vulnerable to invasion (Lonsdale, 1999; Colautti et al., 2006; Catford et al., 2009). Native species are generally adapted to undisturbed habitat conditions, which is contrary to invasive species (Nordheimer and Jeschke, 2018; Khan et al., 2022). The degraded and disturbed habitat therefore becomes less suitable for native species and this decline in native species is filled by invasive species (Hobbs and Huenneke, 1992; Didham et al., 2005).

Habitat disturbance due to human activities, such as road transportation, tourism (Foxcroft et al., 2011a; Anderson et al., 2015; Nath et al., 2019), and streams, creates the dispersal corridors for invasive species and increases their competition with the local vegetation (Parendes and Jones, 2000). Furthermore, roads and tracks result in the fragmentation of the natural areas, which consequentially brings changes in the microclimatic conditions particularly the availability of light (Brothers and Spingarn, 1992; Yates et al., 2004), giving invasive species a competitive advantage. These types of suitable attributes in disturbed and degraded habitats provide an opportunity window for the successful establishment and spread of invasive species (Hobbs and Huenneke, 1992; Ning et al., 2019).

5. Conclusion

It is concluded that environmental variables such as elevation, humidity, and temperature, significantly affect the abundance and distribution of the *Cannabis sativa* in the Western Himalayas in general and Kashmir, Pakistan in particular. Anthropogenic pressures along with habitat disturbance has a prominent role in facilitating cannabis with respect to its abundance and invasiveness. Electrical conductivity is also important among the edaphic factors. The content of organic matter, P and K, has a positive relation with the cannabis abundance. Furthermore, the proportion of the bare land also favors the cannabis establishment. The present study provides useful information in regard to the successful establishment of cannabis in wild habitats. The continuous monitoring program of *C. sativa* would help to control and manage its further establishment in new habitats and thus preserving natural habitats from invasion. Furthermore, future studies should focus on the potential of cannabis invasion at a broader scale and quantification of its impact on biodiversity.

Ethical approval

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CRediT authorship contribution statement

Raposo António: Writing – review & editing, Supervision, Formal analysis. **Lho Linda Heejung:** Writing – review & editing, Data curation. **Han Heesup:** Writing – review & editing, Data curation. **Ain Qurat Ul:** Writing – review & editing, Data curation. **Ahmad Zeeshan:** Software, Data curation. **Khan Shujaul Mulk:** Writing – review & editing, Supervision, Formal analysis. **Ejaz Ujala:** Software, Data curation. **Jehangir Sadia:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Author contributions

All authors contributed to the study's conceptualization and design. **SJ** performed conceptualization, field data, methodology, data analyses and writing original draft. **SMK (as a Ph.D. supervisor of SJ) and AR** did overall supervision, interpretation of data and finalization of the paper draft. **ZA and UE** performed the data analyses and designing through R-software. **QUA, LHL and HH** helped in soil analyses, editing and data curation. All authors read and approved the final submission of the manuscript to Global Ecology and Conservation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02779.

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