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Invasive *Ageratina adenophora* (Asteraceae) in Agroecosystems of Kumaun Himalaya, India: A Threat to Plant Diversity and Sustainable Crop Yield

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Abstract: Invasive plant species pose a serious threat to agricultural yield, although how the threat varies with the distance of crops from invasive plants remains unclear. Therefore, utilizing this viewpoint, objectives were formulated to quantify differences in the native vegetation and performance of crops growing near *A. adenophora*–invaded (treatment plots) and uninvaded ridges (control plots) in the terraced agricultural fields of Kumaun Central Himalaya. Morphological and yield parameters of two crops, viz. rice (*Oryza sativa* L.) and soybean (*Glycine max* L.), were assessed systematically by laying parallel transects from the ridge of the field up to 5 m towards the centre of the field in three equal distance intervals of 1 m in the order: 0–1 m, 2–3 m, and 4–5 m. Crofton weed showed 95–100% crown cover throughout invaded ridges/risers of terraced fields, with stem densities of 134–208 ind. m^{-2} and an average basal area of 0.15 cm^2. The total mean density of herbs (other than *A. adenophora*) in invaded ridges/risers decreased by 38–85% compared to uninvaded ridges, but species richness increased by 31–37%. Soil nutrient availability was high across invaded ridges/risers as well as crop fields. The average irradiance level near uninvaded ridges was 19.6 ± 1.80%, and near invaded ridges, it was 1.8 ± 0.31%. Compared to straw, root, and grain yields obtained at the farthest distance, the yield of rice near uninvaded ridges was reduced by 27%, 19%, and 33%, while near invaded ridges, it was reduced by 37%, 39%, and 43%, respectively; the yield of soybean near uninvaded ridges declined by 62%, 66%, and 42%, while near invaded ridges, it decreased by 59%, 69%, and 47%, respectively. Compared to the values obtained at the farthest distance, the harvest index (HI) of rice near ridges was reduced by 7% and 13%, while the HI of soybean increased by 15 and 10% across uninvaded and invaded field ridges, respectively. The findings indicated that the Crofton weed could suppress field crops and could form a single dominant population in the invaded area, causing a serious threat to the plant community, its diversity, and the yield of the native agroecosystem in the foreseeable future if timely management actions would not be taken.

Keywords: *Ageratina adenophora*; allelopathy; competition; invasion; terraced fields; yield

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1. Introduction

Agriculture and related activities play a significant role in the lives of the Himalayan economy. A majority of these activities are centred between 1200 and 2000 m above sea level (mid–hill zone), where agriculture and allied activities account for about 80% of the rural economy [1,2]. The region differs in terms of topography, cropping patterns, agricultural practices, and in many more ways. Traditional agricultural practices depend heavily on forest–derived resources (vegetative materials such as fodder and bedding leaves, and animal wastes) and are prominently subsistence–based without any commercial interest [2–4]. Production is meagre as the area under arable land is extremely limited and fragmented, with poor irrigation facilities [4]. Due to the low agricultural productivity and ecological difficulties in the region, traditional agriculture practices are gradually changing, and chemical fertilizer and pesticide application rates are rising [4–6]. Further, the introduction of invasive weeds caused by cropland damage as a result of climate change and rising global temperatures is contributing considerably to the already declining agricultural productivity [7]. The ingression of invasive weeds in and around croplands has emerged as a noticeable threat to the existing agricultural as well as natural biodiversity of the area, which in addition, are also promoting the establishment of other alien species over native species [8].

The agricultural lands in the region are extensively terraced. The terraced fields have top flat arable land with ridges (boundaries) and risers (vertical walls), which typically are either bare or are covered by natural vegetation [9] and are primarily maintained for forage production. The ridges and risers of the terraced fields also serve as a suitable habitat for many invasive weeds. Most of the weeds are used as feed for livestock, but some unpalatable weeds, such as *Lantana camara* L. and *Ageratina adenophora* (Spreng.) R. King and H. Rob, are either left untreated or pruned/uprooted. Pruned parts of some vegetatively propagating weeds re–sprout and grow again. Weed remains left untreated could create problems as the leaching of allelochemicals (secondary metabolites) from the decomposing remains might affect the regeneration and growth of native plants growing in its vicinity [10]. The invasive weeds forming dense monospecific stands interrupt the regeneration and establishment of native plants [11], especially plants growing on the ridges and risers.

Most invasions start in anthropogenic environments, such as agricultural systems, due to high anthropogenic disturbance, nutrient availability, and poor sanitary and phytosanitary measures [12]. Invasive weeds often compete with crops for light, water, and nutrients and reduce agricultural productivity by inhibiting seed germination and growth [13]. Studies have revealed that 34% of losses in agricultural production are due to weeds [14], in addition to pests and diseases. In India, a 31.5% reduction in crop yield was estimated to be the result of weeds [12]. Gharde et al. [15] reported that weeds are to blame for an estimated US$ 11 billion in agricultural losses in 10 of India's primary crops.

A. adenophora, also known as 'Crofton weed,' is one such widespread invasive weed found in both natural and agricultural landscapes around the world [16]. This multi–stemmed perennial weed is indigenous to Mexico and the Costa Rica region of Central America [17]. In recent years, this weed has severely invaded the tropical, sub–tropical, and sub–temperate regions of more than 40 nations, including the highlands of the Indian Himalayan Region (IHR) [18] and peninsular India [19], and is still spreading endlessly and threatening native species diversity and ecosystem functioning. In the hilly terrain of Central Himalaya (part of IHR), well–established dense monospecific stands of this weed can be observed along the ridges and risers of the terraced fields as well as in fallow and abandoned agricultural fields. In extensively managed crop fields, its presence is, however, limited at the boundaries. As per Rawat et al. [7], Crofton weed is becoming a serious threat to crop productivity in addition to the natural vegetation growing along the agricultural lands.

One of the ways that Crofton weed affects other plants is by allelopathy [20]. Several allelochemicals or secondary metabolites reported in above and belowground parts of this plant have a role in inhibition. Numerous experimental studies have substantiated that leachates prepared from above and belowground parts of Crofton weed have a strong allelopathic effect on native species as well as in crops [10,21–23]. As Crofton weed grows near crop fields, it may release leachates through rainwater that can be mixed into the field soil. In addition, fallen plant parts of Crofton weed also get mixed with soil and can affect the associated plants. Crofton weed is also a strong competitor as it shows rapid growth rates, which allow this species to outgrow or swiftly crowd out native ground vegetation and affect soil properties [24]. Previous studies have reported negative effects of Crofton weed on the growth and development of native species and crop plants [10,25]; however, impact assessments of Crofton weed on agricultural fields or as weeds of crops are still at rudimentary levels and require scientific studies.

The relative importance of above and belowground competitive interactions in determining the impacts of invasive plant species on native species is unclear under high soil–nutrient environments [26]. Belowground competitive interactions between –crops and weeds are generally for water and nutrient acquisitions, while aboveground, competitive interactions are for harnessing maximum sunlight [27]. Crofton weed is considered a suppressive weed, affecting the growth and establishment of native species through both competition and allelopathy [10,22,28]. However, it is not clear which interaction, competitive or allelopathic, contributes more to the competitive superiority of the weed and how these interactions translate towards crop performance. Therefore, we hypothesized that Crofton weed and native grasses growing on the ridges or risers would differ in their interactions and that these differences would be evident in the performance of crops growing in their vicinity. The main objectives of this study were to quantify the impact of Crofton weed on (i) the soil and vegetation of ridges and risers and (ii) the performance of two economically important crops with increasing distance from Crofton weed–invaded ridges and risers.

In the Kumaun Himalayan region (part of Central Himalaya), crops are cultivated in two types of agricultural land—Upraun (rainfed) and Talaun (irrigated) land. The main crops cultivated in the Upraun land are coarse grains, such as millets, pulses, dry seeded rice, barley, wheat, and soybeans, while, in Talaun land, the main crops are rice, wheat, barley, mustard, potato, etc. [29,30]. The available arable land is cultivated throughout the year. The main crop seasons in the study area are the Kharif (May–June to September–October) and Rabi seasons (Nov.–Dec. to March–April). The main crops of the Kharif season are rice, finger millets, horse gram, and soybean, while wheat, barley, mustard, pea, lentil, and gram are the main crops of the Rabi season [30]. For the present study, field assessment was undertaken during the Kharif season for two crops: a cereal crop–a Kapkoti variety of rice (*Oryza sativa* L.)—and a legume crop–soybean (*Glycine max* L.)

2. Materials and Method

2.1. Description of the Study Site

The study was conducted across the terraced agricultural fields of Majhkhet Village, located at the Kapkot block of the Bageshwar District in Uttarakhand State, India. The study sites are located 70 km north–east from the district headquarters of Bageshwar between 1207–1227 m above sea level (79°22′45.09″ E–79°22′46.85″ E longitude and 29°22′14.39″ N–29°22′16.18″ N latitude) (Figure 1a).

The agricultural lands in the study area are extensively terraced. These terraced agricultural fields typically consist of a top flat arable land, where farmers cultivate traditional crops, which is limited by a boundary/ridge over a vertical wall/riser and a narrow walking path (used during agricultural operations) at the edge of each terrace, and that also delineates ownership [29]. The ridges and risers of the terraced fields are either bare or covered by natural vegetation [9] and are primarily maintained for forage production (Figure 1b–d). As opposed to community–managed grasslands, the yield of forbs and grasses is relatively inferior on the ridges and risers of the terraces. Nonetheless, they represent an integral component of forage production systems and sustain the short–term forage and fuelwood demand of subsistent households.

The study was conducted during June–October 2021 in the Kharif season. From the period of sowing (May) to harvesting (September), the study area experienced a cumulative precipitation of 2602 mm, with a maximum precipitation of 679 mm (July) and 82% relative humidity (August). The maximum monthly temperature fluctuated from 20.9 °C (May) to 23.4 °C (June), while the minimum temperature fluctuated from 12.5 °C (May) to 17.7 °C (July) [31].

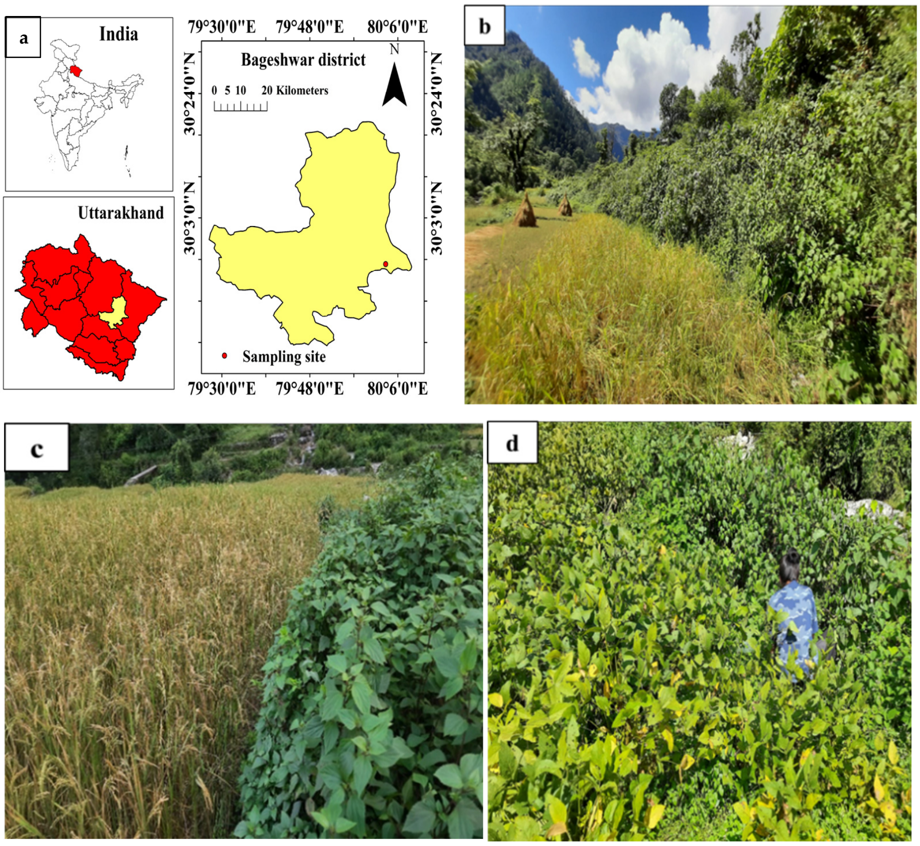

Figure 1. (**a**) Location map of the study site, (**b**–**d**) Crofton weed invaded ridges and risers of the study area.

2.2. Experimental Design

Based on a preliminary survey, two comparative terrace field ridges, one invaded with Crofton weed and having more than 75% crown cover and one without its presence were selected and considered as treatment and control plots, respectively. These are hereafter referred to as invaded ridges (IR) and uninvaded ridges (UR). IR and UR agricultural fields were located in the same land management unit, experiencing similar climatic and topographic conditions (elevational zone, slope, and aspect). Agricultural fields sampled in this study were 1.5–5 m wide, 50–100 m long across the slopes, and 1–2 m high.

2.2.1. Ridge/Riser Vegetation Sampling

The ridges/risers were sampled by randomly placing a total of 27 quadrats of 1×1 m^2 size. The stem diameter was measured at 2 cm above ground level. The ground surface occupied by the herb layer was calculated as total basal area (TBA cm^2 m^{-2}) following Curtis and McIntosh [32] and Misra [33]. The ecological parameters were quantitatively examined for vegetation composition by evaluating density, frequency, abundance, and importance value index (IVI), also following Curtis and McIntosh [32] and Misra [33]. To understand the spatial distribution pattern of species, the abundance to frequency (A/F) ratio was estimated following Cottam and Curtis [34], where a value <0.025 showed regular, a value between 0.025–0.05 showed random, and a value >0.05 showed a contagious pattern. To assess the diversity indices, Shannon's diversity index (H′) was calculated following Shannon and Weaver [35]. Simpson's concentration of dominance (Cd) [36], Margalef's index of richness (R) [37], and Pielou's evenness or equitability (E) [38] were calculated. The index of similarity (IS) was calculated following Muller–Dombois and Ellenberg [39]. Plant species sampled were identified, and nomenclature was verified with the help of taxonomists, different floras, and the previous literature on flowering plants of studied sites in Central Himalaya [40].

2.2.2. Assessment of Crop Density

In this study, the stem density of rice and soybean crop was quantified at the maturation stage. In the study area, rice is cultivated in irrigated terraced fields as a transplanted crop under rainfed conditions. After transplantation, the planting density of rice can vary due to the number of tiller emergences. The planting density of crops was evaluated as per Shahi et al. [2]. For the assessment of stem density of rice (tillers) and soybean, systematic sampling was performed in three equal intervals of 1 m, with distances of 0–1 m, 2–3 m, and 4–5 m from the field ridges up to 5 m towards the centre of the field. For rice, 18 quadrats, and for soybean, 15 quadrats of 50 × 50 cm were laid at each distance interval. Overall, 108 quadrats for rice (2 treatments × 3 distances × 18 quadrats) and 90 for soybean (2 treatments × 3 distance × 15 quadrats) were evaluated in the study. For the assessment of growth and yield parameters, 3 main tillers of rice from randomly selected hills and 3 stems of soybean were harvested (with grains) per 50 × 50 cm quadrat at the maturity stage or full heading stage. Hence, a total of 108 rice tillers (2 treatments × 3 distances × 6 quadrats × 3 tillers) and 90 soybean stems (2 treatments × 3 distances × 5 quadrats × 3 tillers) were harvested for the assessment.

2.2.3. Morphological Parameters

Growth parameters of crops such as shoot length (SL) and root length (RL) were taken using a ruler, whereas stem diameter (SD) was taken at a collar height of 2 cm using a vernier calliper of 0.01 accuracy. SL of the rice tillers was taken from the base of the plant to the top of the panicle.

2.2.4. Yield and Yield–Related Parameters

Yield parameters, such as panicle length (PL), were taken using a ruler, and spikelets per panicle (SPP) were counted. Straw, root, and total grain yields were assessed using an electronic balance after oven–drying samples at 70 °C for 72 h. Manual counting was conducted for each sample to assess grain number per plant. Harvest index (HI) was calculated as the ratio of grain number to total aboveground biomass as a measure of reproductive efficiency following Porker et al. [41]. HI is a trait used as a measure of the reproductive efficiency of crops. It is defined as the capacity of plants to allocate photosynthetic assimilates (biomass) into reproductive parts [42]. The allocation pattern of biomass was assessed as root weight to shoot weight ratio (R:S) as per Khatri et al. [10]. Specific root length (SRL) was evaluated as the ratio of root length to root mass (cm g^{-1}) as per Kaur and Singh [43].

2.2.5. Soil Sampling and Analysis

Soil samples were randomly collected from the ridges as well as from each distance interval (0–1 m, 2–3 m, and 4–5 m) of treatment fields in a replication of three. A total of 12 soil samples (2 treatment fields × 3 replicates × 2 crop field ridges) were collected from ridges while, across crop fields, a total of 36 soil samples (3 distance intervals × 2 treatment fields × 3 replicates × 2 crops) were collected from 0–15 cm depth using a metal corer with a diameter of 5.3 cm. Collected soil samples were mixed thoroughly to form a composite sample of each distance interval. After packing and transporting the samples to the laboratory, the soil samples were then air–dried to analyse the –soil's physicochemical properties.

The soil texture was determined using sieves of different pore sizes: for gravel –> 2.0 mm, sand 0.02–2.0 mm, silt 0.002–0.02 mm, and clay < 0.002 mm were used. The proportion of soil particles was calculated by weight [33]. Soil bulk density (BD) was calculated as the ratio of dry weight to volume of metal corer following Bargali et al. [44]. Soil moisture content (SMC) was evaluated gravimetrically by drying soils till a constant weight was achieved and expressing water content as a percentage of the dry weight. Soil pH was determined in a 1:5 mixture of soil and distilled water using a digital pH meter (Systronics pH system 361). Soil organic carbon (OC) was estimated using the rapid titration method of

Walkley and Black [45] following Jackson [46]. Total soil nitrogen (TN) was determined by the Kjeldhal digestion technique using aKEL PLUS nitrogen analyser (Pelican Equipments, Chennai, India) following Jackson [46]. Available phosphorus (P) was determined by using aUV–VIS spectrophotometer 119 (SYSTRONICS, New Delhi, India) following Olsen's method [47]. Available potassium (K) was determined by using a flame photometer 128 using the neutral normal ammonium acetate method of Black [48].

2.3. Data Analysis

Primary data were further assessed using MS Excel 16.0. Non–normal variables were either log transformed or square transformed to achieve near–normal distribution. The uncertainty factor ($^{F}U_{meas}$) for measured parameters was also assessed. An independent *t*–test was performed to evaluate significant (if any) differences between treatment plots on measured parameters. A one–way ANOVA was performed to assess the effect of distance on measured plant traits using SPSS 22.0. A two–way ANOVA was performed to assess the interaction of treatment and distance on measured traits. A Pearson's correlation test was performed separately for crops to assess the correlation between independent and dependent variables. Further, a multiple linear regression (MLR) analysis was performed to assess the effect of distance and treatment on morphological, yield, and yield–related parameters.

3. Results

3.1. Effect of Invasion on Composition, Structure, and Soil Characteristics of Ridge Vegetation

The floristic survey of the selected ridges documented 28 species, with 26 genera belonging to 15 families (Supplementary Tables S1 and S2). The number of species ranged from 10–12 in uninvaded sites and 12–18 in invaded sites. In uninvaded ridges, around 73% of the herbs analysed were native and 27% were invasive, while in invaded ridges, 68–74% of the herbs were native and 26–32% were invasive. The maximum number of species were recorded in the family Poaceae (8 members), followed by Asteraceae and Cyperaceae (represented by 3 members each), and Urticaeae, and Commelinaceae (represented by 2 members each). The rest of the 10 families were monotypic and were represented by one member each. Vegetation along uninvaded ridges/risers were mainly dominated by forage grasses such as *Crysopogon gryllus*, *Bothrichloa pertusa*, *Digitaria ciliaris,* and *Saccharum bengalense*; sedges such as *Cyperus iria, Cyperus rotundus*, and *Fymbristylis dichotoma;* and forbs such as *Boehmaria cristata*, and *Barleria cristata* together with invasives such as *Ageratum houstonianum* and *Bidens pilosa*. In invaded ridges, grasses such as *Arthraxon nudus*, *Cynodon dactylon*, *S. bengalense*, and *Setaria viridis*; forbs such as *Gonostegia hirta* and *B. cristata*; and invasives such as *A. houstonianum* and *B. pilosa* were common. Comparatively, invaded ridges had 20–50% more invasive species than uninvaded ridges. Dominance was assigned to species on the basis of the importance value index (IVI), and the values of individual species are given in Supplementary Tables S1 and S2.

In the herb layer of invaded ridges, Crofton weed demonstrated a crown cover of 95–100% with stem density of 134–208 individuals $m^{-2,}$ accounting for 65–83% of the total density of the herb layer and an average basal area of 0.15 cm^2. Aside from Crofton weed, the total mean density of herbs in invaded ridges was comparatively lower (36–85%) than in uninvaded ridges, except for the total basal area. The density of herbs (other than Crofton weed) differed significantly ($p < 0.05$) between comparative ridges of soybean fields; however, differences were insignificant across rice field ridges. Based on the A/F ratio, the majority of herb species were contagiously distributed in ridges/risers. The index of similarity (IS) revealed that paired plots were 48–82% similar in species composition. Shannon's diversity (H') and evenness (E) of ridge vegetation showed variable patterns across invaded ridges, while the concentration of dominance (Cd) showed reduction across invaded ridges. Compared to uninvaded ridges, Margalef's species richness (R) increased by 31–37% in IR fields and differed significantly ($p < 0.05$) (Table 1).

Table 1. Vegetative and soil parameters of uninvaded (UR) and invaded (IR) ridge/riser vegetation in the study sites.

Parameters	Rice					Soybean				
	UR	**IR**	***t***	**d.f**	**Sig. (2–Tailed)**	**UR**	**IR**	***t***	**d.f**	**Sig. (2–Tailed)**
Vegetative										
Density	138.44 ± 17.37	88.56 ± 12.22	2.35	4	0.079	234.33 ± 34.51	34.93 ± 3.70	5.75	4	**0.028**
TBA	8.64 ± 1.71	9.65 ± 2.93	−0.30	4	0.781	6.58 ± 0.95	11.77 ± 7.93	−0.65	4	0.581
H′	1.77 ± 0.15	1.04 ± 0.06	4.26	4	**0.013**	1.04 ± 0.17	1.06 ± 0.05	−0.18	4	0.869
E	0.74 ± 0.06	0.37 ± 0.02	5.16	4	**0.007**	0.27 ± 0.14	0.33 ± 0.09	−0.41	4	0.703
CD	0.24 ± 0.04	0.01 ± 0.00	6.10	4	**0.004**	0.55 ± 0.08	0.004 ± 0.00	6.66	4	**0.022**
R	1.66 ± 0.03	2.64 ± 0.13	−7.09	4	**0.002**	1.42 ± 0.10	2.07 ± 0.10	−4.65	4	**0.010**
Soil										
Gravel (%)	47.90 ± 1.78	56.82 ± 1.68	−3.65	4	**0.022**	78.10 ± 0.78	63.52 ± 1.72	7.73	4	**0.002**
Sand (%)	15.90 ± 0.54	14.09 ± 0.44	2.61	4	0.060	6.90 ± 0.67	11.93 ± 0.58	−5.65	4	**0.005**
Silt (%)	9.60 ± 0.33	7.10 ± 0.37	5.07	4	**0.007**	3.43 ± 0.47	7.70 ± 0.99	−3.88	4	**0.018**
Clay (%)	26.61 ± 0.91	21.99 ± 1.02	3.38	4	**0.028**	11.57 ± 0.63	16.84 ± 0.99	−4.49	4	**0.011**
ST (° C)	22.67 ± 0.33	22.67 ± 0.33	0.00	4	1.000	23.67 ± 0.88	22.00 ± 0.58	1.58	4	0.189
SMC	18.33 ± 1.50	21.52 ± 2.22	−1.19	4	0.301	46.95 ± 2.18	42.39 ± 0.68	2.00	4	0.116
BD (g cm^{-3})	1.33 ± 0.04	1.19 ± 0.04	2.60	4	0.060	1.03 ± 0.04	0.90 ± 0.00	3.77	4	0.062
Porosity (%)	48.84 ± 1.71	54.30 ± 1.35	−2.50	4	0.067	60.45 ± 1.41	65.56 ± 0.11	−3.62	4	**0.022**
OC (%)	1.88 ± 0.02	1.96 ± 0.04	−1.91	4	0.129	2.24 ± 0.02	2.80 ± 0.01	−24.29	4	**0.000**
pH	6.20 ± 0.03	7.39 ± 0.07	−15.14	4	**0.000**	7.52 ± 0.02	7.53 ± 0.01	−0.26	4	0.811
TN (%)	0.30 ± 0.01	0.33 ± 0.02	−1.56	4	0.195	0.32 ± 0.01	0.39 ± 0.01	−6.06	4	**0.004**
P (%)	0.0017 ± 0.00	0.0041 ± 0.00	−4.22	4	**0.045**	0.0051 ± 0.00	0.0047 ± 0.00	3.05	4	**0.038**
K (%)	0.0036 ± 0.00	0.0051 ± 0.00	−7.89	4	**0.001**	0.0044 ± 0.00	0.0056 ± 0.00	−5.34	4	**0.006**

Where, significant values (at $p < 0.05$ level) are represented by bold digits; d.f–degree of freedom; TBA—total basal area in $cm^2\ m^{-2}$; H′—Shannon's diversity; E—evenness; CD—concentration of dominance; R—Margalef's species richness; ST–soil temperature; SMC–soil moisture content; BD–bulk density; OC–organic carbon; TN–total nitrogen; P—available phosphorous; K–available potassium.

The majority of the soil physicochemical properties differed significantly between invaded and uninvaded ridges (Table 1). The soil was clayey in texture in both comparative plots; however, textural classes differed significantly ($p < 0.05$) between ridges. Soil moisture, temperature (ST), and bulk density (BD) did not differ significantly between ridges. Soil pH was high across invaded ridges and differed significantly ($p < 0.05$) between ridges. Chemical properties such as organic carbon (OC), total nitrogen (N), phosphorous (P), and potassium (K) content were relatively high across invaded ridges.

3.2. Effect of Invasion on Light Intensity

The vegetation near ridges caused an array of irradiance levels under their canopy. The average irradiance near uninvaded ridges was 19.6 $\pm$ 1.80% and invaded ridges was 1.8 $\pm$ 0.31%. Percent irradiance near ridges was significantly different ($p < 0.05$) between the control and treatment plots.

3.3. Effect of Invasion on Field Crops

Irrespective of the treatment (uninvaded and invaded ridged fields), the majority of morphological and yield–related parameters of crops showed significant reduction near ridges. Treatment– and distance–wise, the majority of the traits differed significantly ($p < 0.05$); however, their combined interaction yielded few significant variations. A detailed description of the uncertainty factor ($^{F}U_{meas}$) for morphological, yield, and yield–related measurements is given in Supplementary Table S3.

3.3.1. Planting Density

The planting density of both crops increased significantly with increasing distance from ridges in the order 0–1 m < 2–3 m < 4–5 m, with the lowest values recorded in IR fields. Rice tiller density in UR and IR fields ranged from 203 to 253 tillers m^{-2} and 198 to 278 tillers m^{-2}, respectively; hill density ranged from 81 to 95 hills m^{-2} and 64 to 97 hills m^{-2}, respectively (Figure 2). The density of rice tillers/hills remained the same, with an average of 3 tillers/hills, and did not vary across treatment and distance intervals.

Similarly, the stem density of soybean varied from 19–42 stem m^{-2} and 15–46 stem m^{-2} in UR and IR fields, respectively.

3.3.2. Morphological Parameters

Examination of the data clearly indicates distance had a significant impact on crop length, which significantly increased with increasing distance from the ridge (Supplementary Figures S1 and S2). However, when compared between fields, the crop height of both crops in IR fields showed a reduction. Except for rice shoot length, results were otherwise insignificant.

3.3.3. Yield and Yield–Related Parameters

Distance had a significant effect on rice panicle length (PL) and spikelet per panicle (SPP), soybean pod number (PN), and pod yield (PY). The lowest values of PL, SPP, PN, and PY were recorded for crops growing adjacent to invaded ridges (Supplementary Figures S1 and S2).

Similarly, the straw, root, and grain yields of both crops substantially declined near ridges. Compared to straw, root, and grain yields obtained at the farthest distance, the yield of rice near ridges was reduced by 27, 19, and 33% in UR fields and by 37%, 39%, and 43%, respectively, in IR fields (Figure S1), whereas the yield of soybean declined by 62%, 66%, and 42% in UR fields and by 59%, 69%, and 47%, respectively, in IR fields (Supplementary Figure S2). The yield of crops near invaded ridges showed a significant reduction over UR fields. Compared to UR fields, straw, root, and grain yields of rice near invaded ridges were reduced by 44%, 55%, and 40%, respectively, while root and grain yields of soybean declined by 10 and 22%, respectively. The observed reduction may be attributed to the rapid and luxuriant growth of Crofton weed along the ridges. Distance showed a positive correlation with rice (r = 0.31, $p > 0.05$) and soybean planting density (r = 0.96, $p < 0.001$) (Supplementary Figure S3a,b).

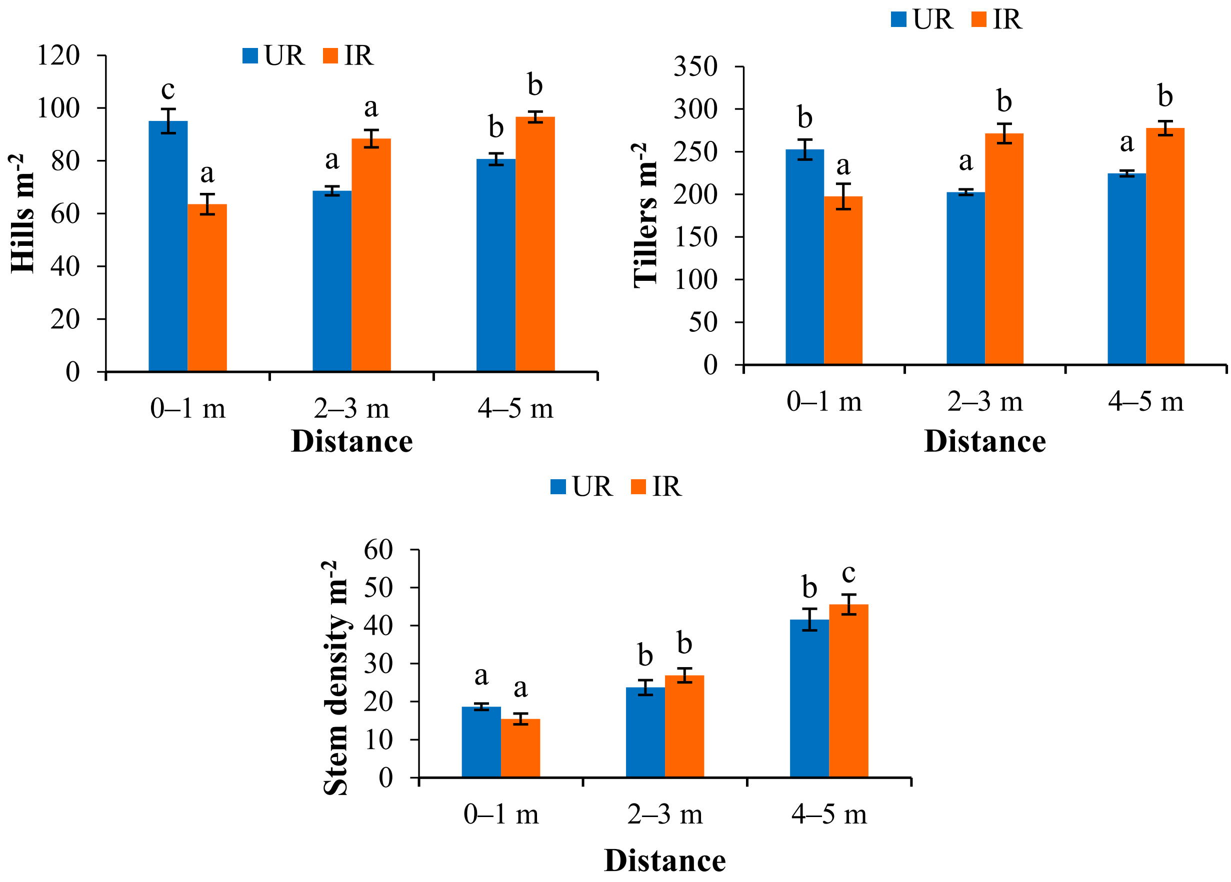

Figure 2. Impact of distance from ridges on planting density of crops in uninvaded (UR) and invaded (IR) crop fields, different lowercase letters above bars represent significant differences between distance intervals for UR and IR separately.

The harvest index (HI) of rice ranged from 0.38–0.41 and 0.38–0.48. For soybean, it fluctuated from 0.35–0.41 and 0.40–0.44 in UR and IR fields, respectively (Supplementary Figures S1 and S2). Compared to values obtained at the farthest distance, the HI of rice near ridges was reduced by 7 and 13%, while the HI of soybean increased by 15 and 10% across UR and IR fields, respectively. Treatment–wise, the HI of soybean differed significantly, while no differences were observed for rice (Table 2).

The specific root length (SRL) of both crops declined as the distance increased from the ridge; however, the reduction was significant for the soybean crop only (Supplementary Figures S1 and S2). There was a significant positive correlation between treatment and SRL of rice (r = 0.91, $p < 0.05$), whereas there was a negative correlation between distance and SRL of soybean (r = 0.95, $p < 0.01$) (Supplementary Figure S3a,b). Treatment– and distance–wise, biomass allocation patterns of crops showed variable results. The R:S ratio of rice was high near invaded ridges, whereas the inverse trend was observed for soybean. Both crops showed a relatively high R:S ratio across IR fields (Supplementary Figure S3).

Table 2. Summary of Two–Way ANOVA for morphological and yield–related parameters of crops.

Parameters	Rice						Parameters	Soybean					
	Treatment		Distance		Treatment × Distance			Treatment		Distance		Treatment × Distance	
	d.f	F	d.f	F	d.f	F		d.f	F	d.f	F	d.f	F
SL	1	18.73 ***	2	3.64 *	2	0.37 NS	SL	1	1.13 NS	2	314.03 ***	1	0.08 NS
RL	1	0.08 NS	2	2.89 NS	2	1.07 NS	RL	1	4.68 *	2	34.45 ***	1	1.21 NS
SD	1	44.45 ***	2	16.29 ***	2	1.30 NS	SD	1	0.13 NS	2	65.44 ***	1	0.14 NS
PL	1	25.22 ***	2	8.60 ***	2	0.64 NS	PN	1	0.24 NS	2	199.18 ***	1	4.81 *
GN	1	31.19 ***	2	8.19 ***	2	1.90 NS	GN	1	23.45 ***	2	84.33 ***	1	7.11 ***
SY	1	45.52 ***	2	12.34 ***	2	1.10 NS	SY	1	0.00 NS	2	127.25 ***	1	0.13 NS
RY	1	27.54 ***	2	2.74 NS	2	0.06 NS	RY	1	0.03 NS	2	157.39 ***	1	2.15 NS
GY	1	19.85 ***	2	14.12 ***	2	0.44 NS	GY	1	16.39 ***	2	106.17 ***	1	3.97 *
SPP	1	22.95 ***	2	10.31 ***	2	5.16 **	PY	1	9.66 **	2	5.25 **	1	2.46 NS
SRL	1	38.07 ***	2	3.58 *	2	0.25 NS	SRL	1	0.89 NS	2	139.92 ***	1	2.15 NS
HI	1	0.66 NS	2	2.94 NS	2	0.24 NS	HI	1	2.19 NS	2	1.58 NS	1	0.05 NS
R:S	1	5.95 *	2	2.41 NS	2	0.30 NS	R:S	1	11.19 ***	2	9.45 ***	1	0.30 NS
TD	1	7.75 **	2	3.55 *	2	23.67 ***	Density	1	0.65 NS	2	89.57 ***	1	1.89 NS
HD	1	0.31 NS	2	6.51 **	2	42.07 ***							
TPH	1	5.90 *	2	1.12 NS	2	1.83 NS							

Where— ***—significant at $p < 0.001$, **—$p < 0.01$, *—$p < 0.05$; NS—non–significant; TD—tiller density; HD—hill density; D— stem density; SL—shoot length; RL—root length; PL—panicle length; SPP—spikelets per panicle; PN—pod number; PY—pod yield; SY—straw yield; RY—root yield; GY—grain yield; SD—stem diameter; HI—harvest index; R:S—root–to–shoot ratio; SRL—specific root length; TPH—tillers per hill.

Multiple linear regression (MLR) analysis showed that distance and treatment had a significant impact on the majority of morphological and yield–related parameters of both crops. However, in the case of rice, the tested value showed a low to moderate correlation coefficient R^2 (i.e., 0–41% variance) with $p < 0.05$; for soybean, the tested value showed a low to high correlation coefficient R^2 (4–81% variance) with $p < 0.05$ (Supplementary Table S6).

3.4. Effect of Invasion on Soil Characteristics of Crop Fields

In rice fields, the texture of soil was clayey, consisting of 43–53% gravel, 14–17% sand, 7–10% silt, and 25–32% clay content, as well as 21–37% soil moisture, 23–26° C soil temperature, 6.4–7.1 pH, 1.14–1.43 g cm^{-3} bulk density, 45–56% porosity, 1.8–2.5% organic carbon, 0.24–0.32% N, 0.0021–0.0053% P and 0.003–0.005% K across treatment and distance intervals (Supplementary Table S4). Treatment, distance intervals, and their combined interaction showed a significant impact ($p < 0.05$) on the majority of physical and chemical parameters of the rice field soil (Table 3). Gravel content declined while sand, silt, clay, and moisture content significantly increased ($p < 0.05$) with increasing distance. The highest values were across the IR fields. Low soil moisture near ridges could be due to low planting density, which might have resulted in evaporation of surface water. BD significantly differed ($p < 0.05$) between treatment fields and was recorded as the lowest across IR fields near ridges together with the highest porosity. In both treatment fields, pH decreased with a surge in distance intervals and shared a positive relationship with organic carbon; however, the relationship observed was insignificant (r= 0.59, $p > 0.05$) (Supplementary Figure S3a,b). Treatment–wise, the highest nutrient stocks were recorded from IR fields. Distance–wise, N and P levels were maximum near ridges except for OC and K levels.

In soybean fields, soil texture was clayey and consisted of 65–76% gravel, 8–11% gravel, 4–6% silt, and 11–19% clay, as well as 4–28° C soil temperature, 6.32–7.68 pH, 1.15–1.48 g cm^{-3} bulk density, 43–56% porosity, 2.13–2.67% OC, 0.25–0.41% N, 0.0021–0.0055% P and 0.0030–0.0052% K across treatment and distance intervals (Supplementary Table S4). Treatment, distance intervals, and their combined interaction showed a significant impact ($p < 0.05$) on soil chemical properties (Table 3). Unlike rice fields, here, gravel content increased while sand, silt, clay, moisture content, soil temperature, and porosity significantly decreased ($p < 0.05$) with increasing distance. Higher values were across IR fields. The highest BD values were recorded at the farthest distance across IR fields.

Similar to the rice fields, pH decreased along distance intervals and was negatively correlated with OC content (r = -0.69, $p > 0.05$) (Supplementary Figure S3a,b). Similar to rice fields, the highest nutrient stocks were recorded from IR fields, whereas N and P content near ridges were comparatively high except for OC and K content. A detailed description of the uncertainty factor (${}^{F}U_{meas}$) for soil –physicochemical–related measurements is given in Supplementary Table S5.

Table 3. Summary of Two–Way ANOVA for soil physicochemical characteristics.

	Rice						Soybean					
	Treatment		Distance		Treatment × Distance		Treatment		Distance		Treatment × Distance	
Parameters	**d.f**	**F**	**d.f**	**F**	**d.f**	**F**	**d.f**	**F**	**d.f**	**F**	**d.f**	**F**
Gravel	1	109.39 ***	2	294.03 ***	2	38.28 ***	1	3.36 ^{NS}	2	81.47 ***	2	2.41 ^{NS}
Sand	1	57.31 ***	2	30.14 ***	2	47.21 ***	1	0.001 ^{NS}	2	15.84 **	2	0.21 ^{NS}
Silt	1	6.57 *	2	1.55 ^{NS}	2	7.08 **	1	2.32 ^{NS}	2	4.87 *	2	0.15 ^{NS}
Clay	1	116.40 ***	2	12.46 ***	2	15.86 ***	1	0.92 ^{NS}	2	62.22 ***	2	4.83 ^{NS}
ST	1	0.17 ^{NS}	2	41.23 ***	2	32.88 ***	1	0.06 ^{NS}	2	40.39 ***	2	1.06 ^{NS}
SMC	1	23.60 ***	2	4.67 *	2	0.67 ^{NS}	1	4.28 ^{NS}	2	4.04 *	2	1.61 ^{NS}
BD	1	100.71 ***	2	140.00 ***	2	37.77 ***	1	0.08 ^{NS}	2	36.62 ***	2	1.19 ^{NS}
Porosity	1	94.20 ***	2	5.97 *	2	13.40 ***	1	0.10 ^{NS}	2	36.51 ***	2	1.19 ^{NS}
OC	1	810.99 ***	2	28.20 ***	2	83.01 ***	1	1.61 ^{NS}	2	304.11 ***	2	28.29 ***
pH	1	48.11 ***	2	10.61 **	2	4.67 *	1	167.92 ***	2	1.50 ^{NS}	2	0.95 ^{NS}
TN	1	7.69 *	2	0.94 ^{NS}	2	4.98 *	1	27.84 ***	2	8.86 **	2	14.70 ***
P	1	1075.00 ***	2	14.81 ***	2	15.79 ***	1	984.02 ***	2	10.25 **	2	8.38 **
K	1	294.03 ***	2	38.28 ***	2	9.78 **	1	94.25 ***	2	41.15 ***	2	27.65 ***

Where ***—significant at $p < 0.001$; **—$p < 0.01$; *—$p < 0.05$; ^{NS}—non–significant; d.f—degree of freedom; ST—soil temperature; SMC—soil moisture content; BD—bulk density; OC—organic carbon; TN—total nitrogen; P—available phosphorous; K—available potassium.

4. Discussion

4.1. Effect of Crofton Weed on Ridge Vegetation and Soil Characteristics

According to Hejda et al. [49], differences in cover and height of the invader and native species can be prime determinants of the degree to which species richness, diversity, and evenness are reduced in invaded communities. The reduction in the density of herb communities, especially forage grasses in invaded plots, clearly implies these sites are becoming less productive and stable. However, contrary to uninvaded ridges/risers, high species richness was recorded in invaded sites despite their low density. Increased species richness and diversity in invaded ridges/risers is either an outcome of the facilitative/neutral effect of an invasive species [50] or a function of localized site disturbances [51]. A surplus of economically insignificant plant species in invaded areas may potentially be the cause of the high species richness and diversity [50]. Previous studies have shown that high pH values could be due to higher uptake of nitrate than ammonium by invasive species [22]. Similar increased soil pH values were obtained in our study; however, differences were significant only for invaded ridges of rice fields. Our results showed high nutrient availability in the invaded ridges compared to the uninvaded ridges, which is in accordance with earlier studies reporting the potential role of Crofton weed in increasing soil fertility and creating favourable conditions for itself [22,52]. Invasive plant species are reported to increase soil nutrient availability [53] and are strongly tied to nutrient cycle activities such as plant biomass accumulation, litter production and decomposition, and soil nutrient alteration [54]. Another aspect explaining the increase in soil nutrient availability is increased soil microbial activity, as they control the rate of nutrient transformation in soil [55]. Invaded soils typically have higher concentrations of inorganic N and higher rates of N mineralization and nitrification [56].

4.2. Variation in Soil Characteristics of Crop Fields

Soil nutrients are important indicators of cultivated land quality, which is determined by two aspects: soil fertility and spatial location [57]. Invasion by alien plants can increase or decrease soil fertility [58,59], which can affect competitive relationships between invasive and native species [60]. This study showed that Crofton weed led to significant changes in soil characteristics, indicating that nutrient cycles change with invasion. In both rice and soybean fields, soil nutrient concentration (OC, total N, and available P and K) increased in invaded plots compared to uninvaded plots. Wang and Li [61] reported that Crofton weed exhibits higher P acclimatization ability than native plants and could grow well under high P levels. At high P levels, the Crofton weed might out–shade native species by increasing plant height, branch/ramet number, and leaf area index, as these attributes create low irradiance levels under its canopy [62]. These enhanced soil P levels might be one of the factors responsible for its invasion success across nutrient–rich sites such as agricultural lands. In the case of soybean crops, grain yield was positively correlated with increased potassium content. Increased photosynthetic activity at the highest rate of potassium availability results in increased grain number per plant and straw yield [63].

Soil pH decreased with a surge in distance intervals and shared a negative relationship with organic carbon. In surface soil, lower pH values are generally a result of the decomposition of the organic matter that leads to the formation of more organic acids, thus, lowering the pH of the surface soil [64]. High soil organic carbon content evaluated at the farthest distance might have resulted in a lowering of the pH. The K content near ridges was relatively low, and studies have shown that a low application rate of K lowers grain yield, probably due to its possible role in translocating carbohydrates to the growing part of the crop resulting in poor yield [65]. In the case of soybean crops, grain yield was positively correlated with increased potassium content.

Moreover, relatively high nutrient stocks in invaded ridged fields are also indicative of the transitioning of the traditional agricultural practices in the study area. In the recent decade, application rates of chemical fertilizers such as NPK, DAP (Di–ammonium Phosphate), urea, etc., have increased rapidly in the region, and excessive quantities are applied to enhance crop yields. Soil properties affect plant productivity as they share a close association with nutrient cycling and plant nutrient uptake [66]. High nutrient stocks might be responsible for relatively high stem density, length, and crop yields observed across fields with invaded ridges compared to fields with uninvaded ridges. In the dissected landscapes of Himalayan agricultural fields, bioclimatic conditions change rapidly and may vary within short distances resulting in a pronounced heterogeneity of soil types and their physical, chemical, and biological properties [4,6].

4.3. Variation in Crop Performance

4.3.1. With Increasing Distance from Ridge

Irrespective of treatments, distance–wise, crop performance differed significantly. Various morphological and yield–related traits differed in response to crop density. Irrespective of the treatment, the stem density of crops increased with increasing distance from the ridge, which significantly contributed to high crop length and productivity. Khatri et al. [10] demonstrated a significant increment in morphological and yield–related traits of millets growing at the farthest distance from Crofton weed–invaded boundaries in their experiment, and our results are consistent with their findings. Yet functional traits such as HI, R:S, and SRL of both crops in the present study showed variable results. The HI value of rice increased while the HI of soybean declined as the distance increased from the ridges. In general, a high HI value translates to a high crop yield as a result of the partitioning of assimilates towards reproductive parts at the expense of unwanted plant parts. The plausible explanation for reduced HI of soybean at the farthest distance is more likely a result of competition for assimilates between reproductive parts and elongated stems having more leaves [67]. The comparatively high stem density of the soybean crop at the farthest distance from adjacent ridges has resulted in more straw yield compared to grain yield, therefore, resulting in low HI. Stem density has a significant impact on grain yield. At high density, the maximum yield per unit area cannot reach its maximum due to high intraspecific competition, while, at low stem density, the yield of a single plant does reach its maximum, but the yield per unit area still decreases due to low stem density [68]. For rice crops, low stem density at adjacent ridges might have resulted in low HI values.

Climate has an impact on every aspect of agricultural production. Cropping intensity and yield are influenced by changes in topographic conditions and monsoonal rainfall [4]. The observed differences in crop yield could be likely influenced by climatic conditions also.

Irrespective of the treatments, there were variations in the root allocation pattern of both crops in response to density depending on edaphic conditions, including (a) a decreased R:S ratio for rice with an increased density in relatively less fertile soil, (b) an increased R:S ratio of soybean with higher densities in fertile soil. High plant density either decreases or shows no impact on root allocation patterns, depending on resource levels [69]. A low R:S ratio for rice with a high stem density indicated that belowground interaction was not intense compared to aboveground competition for light. In low–light environments, plants tend to partition more biomass in aerial parts, resulting in elongation (or etiolation) in order to harvest more light energy [70]. A high R:S ratio is generally observed when the availability of either water or nutrients is limited. Our results demonstrated that the availability of resources declined for soybean crops growing at the farthest distance as the stem density increased. This is likely due to reduced growth spaces between plants and the availability of nutrient resources. Under these conditions, intraspecific competition for belowground resources is high.

Water and nutrient uptake by the root primarily depends on root length or root surface area than mass [71]. Plants with a high SRL tend to invest less biomass to produce root length, which enables them to increase the length of their root system over plants with a low SRL [72]. High–SRL plants have shown higher rates of water and nutrient acquisition than plants with a low SRL. SRL in the present study responded differently to density and edaphic conditions; under high density, rice showed a relatively high SRL in nutrient–rich soil, while soybean displayed low SRL in both nutrient–rich and less fertile soil. The spatial orientation of roots, in response to density, plays a significant role in their propagation. Under high density, the horizontal expansion of roots in the presence of neighbours is restricted; instead, vertical expansion is promoted [69,73]. This horizontal suppression due to the presence of neighbours makes root inefficient in foraging a greater range of satisfactory resources from upper layers of soil [69]; thus, vertical growth of root length is promoted. Differences in the SRL observed could be an outcome of belowground intraspecific interactions. Regardless of treatment, the SRL of crops also responded differently at high density. The high SRL of rice observed might indicate that plants invested less biomass in producing root length while, in the case of the low SRL of soybean, plants invested comparatively more biomass over root length.

4.3.2. Near Ridges

Our results clearly showed a reduction in crop stem density, length, straw, root, and grain yield observed near ridges compared to the farthest distance intervals, which may be attributed to the luxuriant growth of forage grasses and Crofton weed along the ridges. Differences in the competitive interaction of ridge vegetation might have resulted in differential responses from the neighbouring crops. Competitive effects are a function of plant size and growth form, i.e., they are mostly related to mass, where species with greater size exhibit greater competitive effects than grasses [74]. Treatment–wise, crops growing near invaded ridges showed a significant reduction in the majority of measured traits compared to uninvaded ridges indicating the competitive effects of Crofton weed are relatively more severe. Further, unfavourable weather conditions, including drought, severe rain, continuous rain, and extreme temperatures, exacerbate weed–crop interference because the majority of crop varieties are highly susceptible to such climatic influence while weeds are tolerant of similar stresses [75].

Crop and weeds often compete for the same resources, such as nutrients, water, and light [43]. Crofton weeds display relatively high productivity and a rapid growth rate and can achieve a height of 1–3 m [76]. Several studies have reported that invasive plants tend to allocate high biomass towards leaves and shoots [22,77,78], thus, acquiring greater height than their native counterparts. These traits enable Crofton weeds to form dense monospecific stands, creating shade over native plant species. Feng et al. [79] reported less than 2% irradiance under its canopy, which is consistent with our results. Multiple studies have shown a significant reduction in yield under reduced irradiance levels [80,81]. Consistent with our results, the effect of prolonged shading stress on wheat cultivars has shown reduced grain number, grain weight, plant height, and dry matter weight of main stems and tillers [82]. Under prolonged shading conditions, chlorophyll content and photosynthetic activity were reduced, and the number of ineffective tiller and ear sterility rates increased, which subsequently led to a sharp decline in grain yield due to reduced grain number and grain weight [82]. Chen et al. [80] also reported reduced rice yield under low–light intensity. Our study also documented the differential R:S ratio pattern of crops in response to ridge vegetation. Soybeans growing near ridges showed a reduced R:S ratio compared to farthest distances, which was most likely due to reduced irradiance/shading or aboveground interaction, while near the invaded ridge, it was higher than the uninvaded ridge.

Rice growing near ridges showed a relatively high R:S ratio compared to farthest distances, while treatment–wise, the highest values were recorded for uninvaded ridges. Regardless of treatment, competition for belowground resources near ridges might have resulted in a high R:S ratio, probably due to the intense root system of both grasses and weeds of the ridges. Low moisture regimes recorded near uninvaded ridges might also be responsible for a high R:S ratio. In case of low water availability, plants respond by allocating more biomass to roots in order to acquire the limited resource [78].

SRL values of both crops growing near invaded ridge were relatively higher than the uninvaded ridge. As stated earlier, the unavailability of resources on the upper surface of the soil might direct the movement of roots vertically into deeper soils, particularly in the presence of neighbours. The widespread root system of a weed exhibits a higher level of competition with neighbouring plants for soil resources, especially for water and nutrients [43], including grasses. Grasses, due to their fibrous roots, show larger per–gram effects on soil resources [74]. Crofton weed reportedly has a well–developed root system [83], which usually is restricted to surface–subsurface layers of soil, with most of the thick roots confining in the top 8 cm of surface soil [19]. The roots of this weed are extensively branched and predominantly spread laterally or horizontally up to a maximum radius of ~17–85 cm [77,84].

Allelopathic interference of Crofton weed with adjacent growing crops may be responsible for reduced growth and differential R:S and SRL patterns. Allelochemicals (secondary metabolites) affect nutrient uptake by native species, which can be exhibited in the form of nutrient deficiency in growing plants and poor plant growth [85]. Reduced nutrient uptake results in poor growth, fresh mass, root size, dry mass, etc., of the affected plants [86]. Allelochemicals have also been attributed to the reduced uptake of mineral elements by disturbing the functions of the root plasma membranes; depolarizing the gradient of electrochemical potential across membranes; by hindering electron transport and oxidative phosphorylation, which decreases the ATP content of cells; and by altering membrane permeability to mineral ions [87].

The leaves and roots of Crofton weed produce a number of putative allelochemicals that are toxic to crops. Volatiles [88], sesquiterpenes derivatives [89], and quinic acid derivatives have been identified [90]. The allelopathic potential of Crofton weed leaf and root leachate on regeneration and growth of native plants of different habits has been well documented [21–23]. The native/tested plants include a variety of crop species such as *Amaranthus caudatus*, *A. retroflexus*, *Brassica campestris*, *Chenopodium glaucum*, *Hordeum vulgare*, *Lens culinaris*, *Oryza sativa*, *Triticum aestivum*, *Vigna unguiculata*, and *Zea mays* [7,23,91,92]; weeds such as *Ageratum conyzoides*, *B. pilosa*, *Galinsoga parviflora*, and *Cyperus rotundus* [92]; grasses such as Ryegrass [93]; shrubs such as *Osbeckia stellata*, *Elsholtzia blanda* [20], *Berberis asiatica*, and *Rubus ellipticus* [22]; and native tree species such as *Schima wallichii* and *Alnus nepalensis* [21]. However, the response of native plants vary species–to–species towards allelopathic interference of Crofton weed [20]. Leaching of water–soluble allelochemicals from dense foliar cover, root exudates, and litter accumulates might have affected the growth and productivity of the crops growing in its vicinity. In a manner similar to that of allelopathic interference, other invasive species of the Asteraceae family, notably *Solidago gigantea* and *Solidago canadensis*, have reportedly influenced the number and biodiversity of native species in their invaded ranges, including a variety of crop species [94,95]. Those observations might point to the role of allelopathy in the interaction between Crofton weed and native plant species to some extent.

5. Conclusions

Our study has shown differences in the response of crops growing adjacent to ridge vegetation. Regardless of the treatments, both rice and soybean crops growing near ridges performed poorer than at the farthest distance. In terms of interaction, Crofton weed and native grasses growing on the ridges also differed in their interactions. Under high crop density, intraspecific interactions might have prevailed, while interspecific interactions were pronounced near ridges under low density. The synergistic influence of competitive and allelopathic interactions might have aided Crofton weed in attaining competitive superiority over native species and colonizing new areas. The weed will continue to affect the structure and function of the native ecosystem in the foreseeable future if no management actions are taken. The study is preliminary in its stage of investigation, and to understand the prolonged impact of invasive species, long–term monitoring is required to obtain more reliable results. The utilization of bioherbicides can be promoted to reduce the negative role of weeds in crop production. The limitation of arable land is one of the major constraints of terrace agriculture; therefore, it becomes imperative to utilize this limited resource so that it can provide sustainable production to the agrarian economy of the region. The use of shade–tolerant crops near ridges could be advantageous as such crops would perform better even under low irradiance levels. To intensify terrace agriculture, the promotion of wall–climbing or wall–descending crops could be implemented over bare or weed–filled ridges and risers. To broaden terrace farming, formalized government policy and funding for groups committed to the well–being of terrace farmers and ecosystems could help to promote such efforts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151410748/s1, Table S1: Comparative phyto–sociological data of uninvaded (UR) and invaded (IR) ridge vegetation of Rice fields. Table S2: Comparative phyto–sociological data of uninvaded (UR) and invaded (IR) ridge vegetation of Soybean fields. Table S3: Uncertainty factor (FUmeas) for morphological, yield and yield related measurements. Table S4: Physico–chemical characteristics (mean ± S.E) of soil in crop field with uninvaded (UR) and invaded (IR) ridges. Table S5: Uncertainty factor ($^{F}U_{meas}$) for soil physico–chemical measurements. Table S6: Multiple linear regression (MLR) analysis on morphological, yield and yield related parameters of crop. Figure S1: Morphological and yield parameters of rice crop at different distance intervals (0–1, 2–3, 4–5 m) from ridge. Different small letters above bar represent the significant difference at $p < 0.05$ between distance intervals. UR—fields with uninvaded ridges, IR—fields with invaded ridges, SL—shoot length, RL—root length, PL—panicle length, GN—grain number, SPP–spikelets per panicle, SY—straw yield, RY—root yield, GY— grain yield, SD—stem diameter, HI—harvest index, R:S—root to shoot ratio, SRL—specific root length, HI—harvest index, R:S—root to shoot ratio, SRL—specific root length. Figure S2: Treatment wise morphological and yield parameters of soybean crop in different distance intervals (0–1, 2–3, 4–5 m) in study site. Different small letters above bar represent the significant difference at $p < 0.05$ between distance intervals. UR—fields with uninvaded ridges, IR—fields with invaded ridges, SL—shoot length, RL—root length, PL—panicle length, SPP–spikelets per panicle, PN—Pod number, PY—pod yield, SY—straw yield, RY—root yield, GY—grain yield, SD—stem diameter, HI—harvest index, R:S—root to shoot ratio, SRL—specific root length. Figure S3: Pearson correlations between physical and chemical characteristics of soil, morphological and yield parameters of a. rice and, b. soybean crop, where, TD—tiller density, HD—hill density, TPH–tillers per hill, D—stem density, SL—shoot length, RL—root length, PL—panicle length, SPP—spikelet per panicle, GN—grain number, SY—straw yield, RY—root yield, GY— grain yield, SD—stem diameter, HI—harvest index, R:S—root to shoot ratio, SRL—specific root length. Boxed eclipses are significantly different at $p < 0.05$.

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