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Performance of Push–Pull Technology in Low-Fertility Soils under Conventional and Conservation Agriculture Farming Systems in Malawi

Saliou Niassy [1,*], Mawufe Komi Agbodzavu [1,2], Bester Tawona Mudereri [1], Donwell Kamalongo [3], Ivy Ligowe [3], Girma Hailu [1], Emily Kimathi [1], Zwide Jere [4], Nathan Ochatum [1], Jimmy Pittchar [1], Menale Kassie [1] and Zeyaur Khan [1]

[1] International Centre of Insect Physiology and Ecology (ICIPE), Nairobi P.O. Box 30772-00100, Kenya; m.agbodzavu@cgiar.org (M.K.A.); bmudereri@icipe.org (B.T.M.); ghailu@icipe.org (G.H.); ekimathi@icipe.org (E.K.); nathela2010@gmail.com (N.O.); jpittchar@icipe.org (J.P.); mkassie@icipe.org (M.K.); zkhan@icipe.org (Z.K.)
[2] International Institute of Tropical Agriculture (IITA), Haut-Congo, Gombe, Kinshasa 4163, Congo
[3] Department of Agricultural Research Services (DARS), Lilongwe P.O. Box 30779, Malawi; dkamalongo@yahoo.com (D.K.); ivyligowe@gmail.com (I.L.)
[4] Total Land Care Malawi, Area 12, Plot 520, Lilongwe P.O. Box 2440, Malawi; zjere@tlcmw.org
* Correspondence: sniassy@icipe.org

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Abstract: Push–pull technology (PPT) is one of the most viable low-cost agroecological practices that reduces the effects of insect pest infestations (e.g., stemborer) and parasitic weeds (e.g., *Striga*) in croplands. PPT was evaluated in low-fertility soils and two farming practices, minimum-tilled conservation agriculture practice (CA), and conventionally tilled practice (CP), in contrasting agroecological zones at the Chitedze, Mbawa, and Chitala stations in Malawi. Stemborer and *Striga* infestations were also investigated and the suitability levels of two *Desmodium* species. Farmers' perceptions of PPT were gathered through a focus group discussion. The performance of PPT varied significantly between treatments, sites, and years on grain yields and the number of cobs that could be assigned to soil attributes. Significant variations were found in the number of exit holes, stemborer damage severity, and the number of *Striga*-affected plants with severe infestation. In Chitedze, CP recorded significantly shorter maize plants by 14.1, 11.6, and 5.8 cm than CP–PP, CA, and CA–PP, respectively, in 2016–2017. There were no significant differences in plant height between CP–PP, CA, and CA–PP. Similar results were also found in 2017–2018. Focus group discussions among farmers attested to up to 70% reductions in *Striga* weed and stemborer pests under PPT over the two seasons. Farmers who used push–pull technology reported a 45–50% yield increase. Push–pull was also perceived as a technology that improves soil fertility and controls soil erosion. The study presented the importance of soil physicochemical properties in the performance of the technology, as supported by the high occurrence of *Striga asiatica* in the country and the low suitability of Greenleaf *Desmodium*. Results reaffirmed the technology's agronomic benefits in productivity, pest management, plant vigour, and *Striga* control. The cost of labour was described as a challenge, and research to identify more suitable *Desmodium* species is needed. The current study suggests the release of the technology in Malawi, emphasizing the inclusion of *Desmodium* and *Brachiaria* as animal fodder for the adoption of the technology.

Keywords: stemborers; infestation; *Desmodium*; *Brachiaria*; *Striga*; maize; yield

1. Introduction

Maize *Zea mays* L. is the staple crop in Malawi and a major source of carbohydrates for over 80% of the Malawian population [1]. Approximately 70% of the land area under cultivation is under maize production each year [2]. Unfortunately, maize production in

Malawi is severely affected by both biotic and abiotic factors. Among the biotic factors, stemborers and the parasitic weed *Striga* sp. are the most common, with the lepidopteran stemborers causing huge maize yield losses [3]. The spotted stemborer *Chilo partellus* Swinhoe (Lepidoptera: Crambidae) and the African stemborer *Busseola fusca* Fuller (Lepidoptera: Noctuidae) are the two most economically important stemborer pests in maize cultivation [4].

On the other hand, *Striga* infestation in Malawi is also widespread [5] and is one of the major constraints limiting maize [6]. *Striga* infestation is severe and affects more than 40% of the maize-cultivated land [7]. Other important factors limiting maize yields in Malawi include low soil fertility and environmental factors, e.g., poor rainfall, heat, and water stress [8].

In Malawi, synthetic chemical pesticides have been traditionally promoted for pest control [9]. However, chemical control is often not successful because the pests burrow out of reach into the stems and hide in the whorls of the plants [10]. Over-reliance on synthetic pesticides leads to ecological and human hazards [9]. Synthetic pesticides are often unaffordable for most African smallholder farmers [11].

Over the past few years, environment-friendly control methods for stemborers have been promoted, including host-plant resistance [12], biological control [13], and habitat management [14,15]. Conservation agriculture (CA) was introduced into Malawi to address many maize-production constraints, based on the perceived benefits for crop yields, soil organic content storage, weed suppression, reduced soil erosion, improved soil water retention [16,17]. However, in the last two decades, Malawi has experienced severe climatic disasters in the form of dry spells, seasonal droughts, intense rainfall, riverine floods, and flash floods with increased frequency, intensity, and magnitude, adversely impacting food security and reducing the benefits of the CA approach [17–19]. Moreover, the recent emergence of the devastating fall armyworm (FAW), *Spodoptera frugiperda* J. E. Smith (Lepidoptera: Noctuidae), has further exacerbated the challenges in maize production in Malawi, forcing the government to declare a state of emergency due to the significance of the losses. The value of FAW losses as a percentage of agricultural GDP in Malawi is estimated at 0.5 percent [20], which is among the highest percentages in the last decade [21].

One of the most successful and viable low-cost agroecological practices being promoted to help curb the problem of insect pests like stemborers and parasitic weeds such as *Striga*, and poor soil fertility, is push–pull technology (PPT). PPT involves trapping stemborers on highly attractive border plants (pull), Napier grass *Pennisetum purpureum* Schumach, or *Brachiaria* cv Mulato II and driving them away. On the other hand, *Desmodium uncinatum* Jacq. (Silverleaf) and *Desmodium intortum* Urb. (Greenleaf), planted between maize rows, repel ovipositing stemborer moths (push) [15,22]. In addition, *Desmodium* enriches the soil with nitrogen and protects it from erosion as it acts as a cover crop, leading to improved maize yields [23–25]. Concurrently, PPT provides high-value animal fodder from the harvest of the companion crops, facilitating increased milk production and diversification of farmers' income sources [26]. Lately, it has been discovered that climate-adapted PPT effectively controls FAW in maize [24,27].

The success of PPT has been attributed to the stimulo-deterrent action of companion crops, which depends on the soil's physicochemical propertiesq [3]. Thus, the suitability of the *Desmodium* species depends on various climatic factors such as temperature and soil type [28]. In contrast, the incidence of *Striga* and other insect pests such as the stemborer and FAW varies according to the agro-ecology zones [29]. These aspects have often been overlooked, yet they are critical for scaling this technology. Moreover, investigating the acceptance and use of the technology is a critical aspect of adoption and scaling. These two components are mainly driven by performance and effort expectancy and influenced by gender, age, and experience [30].

The objectives of this study were (i) to investigate the performance of PPT under current farming practices in various agroecological zones; and (ii) to evaluate the suitability of *Desmodium* species and *Striga* to guide PPT scaling, and (iii) to understand the socio-economic drivers that may influence the adoption of the technology.

2. Materials and Methods

Field experiments were conducted using on-station research sites in Chitala, Chitedze, and Mbawa under unimodal rainfed conditions for three growing seasons between 2016 and 2019, in different contrasting agro-ecologies. On-farm co-validation activities were conducted in Lilongwe, Salima, Nkhotakota, and Mzimba. Figure 1 shows the four agro-ecological regions in Malawi considered in this study.

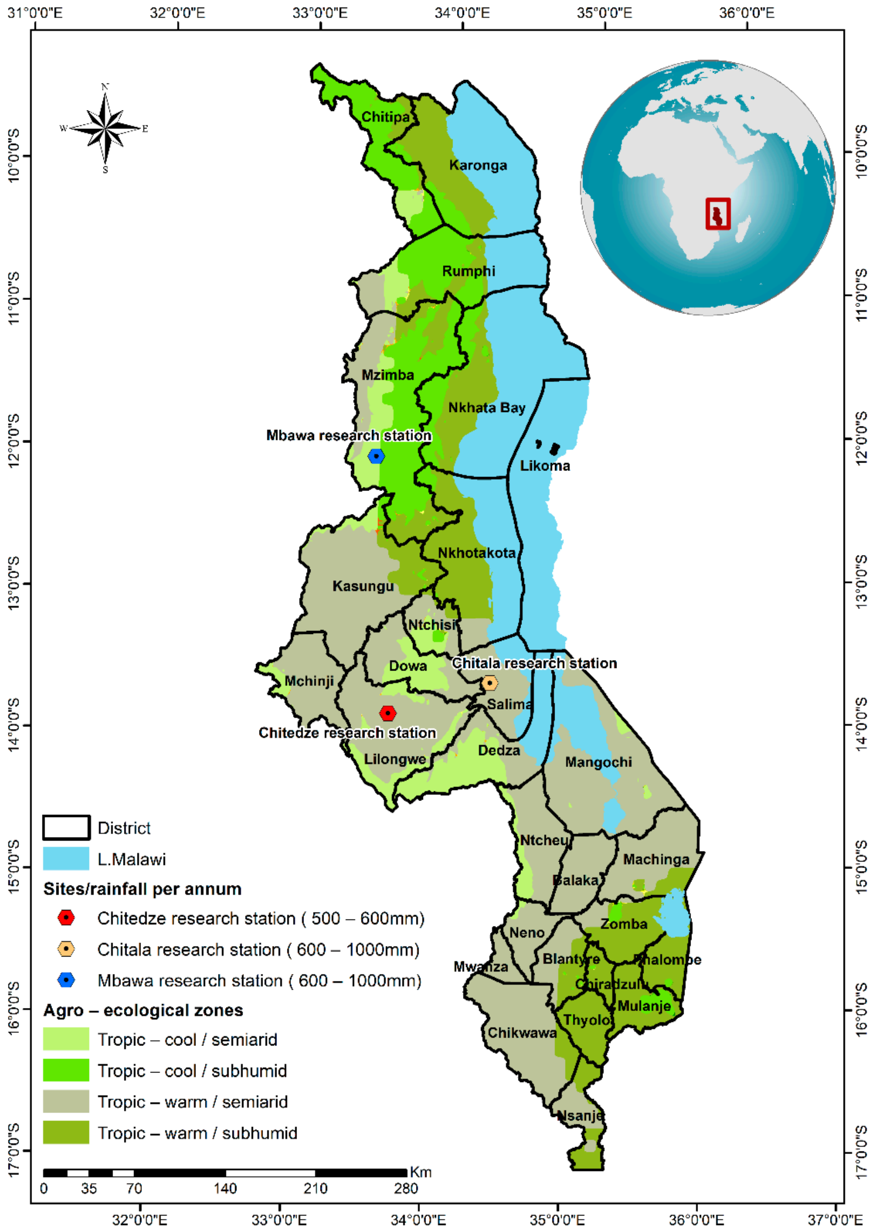

Figure 1. Graphical representation of the four agroecological regions covering the experimental sites in Chitala, Chitedze, and Mbawa research stations.

In Malawi, the rainfall season starts in November–December, which coincides with the planting season of most of the annual crops. The end of the rainfall season is between April and May, which initiates most of the harvesting activities of most crops. Figure 2 shows the rainfall patterns during the three maize growing seasons considered in this study.

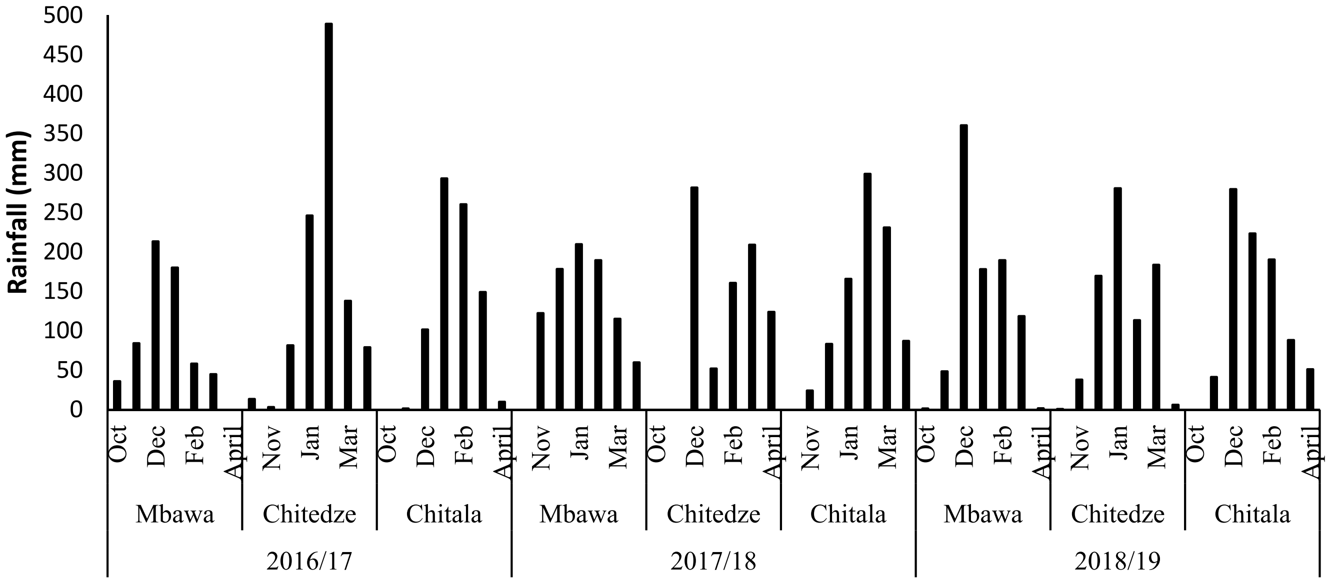

Figure 2. Monthly total rainfall (mm) for the study sites in the 2016–2017, 2017–2018, and 2018–2019 growing seasons in Mbawa, Chitedze, and Chitala, Malawi.

2.1. *Soil Characterisation*

Soil properties are critical for the propagation of *Striga* and the success of the companion crops in a PPT [31]. The physical and chemical soil properties from the topsoil profile (0–20 cm) were analysed from the Chitedze Agricultural Research Station laboratory. Soil samples were analysed for total soil organic carbon (SOC) using the Walkley and Black method described by Anderson and Ingrams [32]. Thesoil organic matter (SOM) and mineralisable N were derived from the SOC and SOM, respectively, by multiplying the percentage concentration with a factor. Phosphorus and exchangeable base cations of K, Ca, and Mg were analysed using the Mehlich 3 method as described in [33]. The results of the analysis are detailed in Table 1.

2.2. *Design, Treatments, and Field Layout*

A set of four plots or treatments shown in Figure 3 were arranged in a randomised complete block design and replicated three times at every site. The plot size was 10 m long × 10 m wide, with 0.75 m between rows. Two of the four plots were sown with maize/*Desmodium* intercropping under CA (CA–PP) and CP (CP–PP), with grass planted at the perimeter of each plot (Figure 3). A 1 m buffer separated the plots from each other. The other two plots were sown with maize mono-cropping under CA and CP. The maize mono-cropping plots were established 5 m away from the maize/*Desmodium* intercropping plots (Figure 3). The intercropping treatments and their corresponding monocrops were sown at a similar maize sowing density to compare them.

Table 1. Physico-chemical soil properties at the end of the growing season.

Site	Treatments	pH	%OC	%OM	%N	P (μg/g)	K Cmol/Kg	Ca Cmol/Kg	Mg (Cmol/Kg)	% Sand	% Silt	% Clay	Texture
Mbawa	CP sole maize	5.90	0.43	0.74	0.04	31.75	1.17	0.127	3.87	76	6	18	Sandy Loam
Mbawa	CA + PP	5.14	0.63	1.08	0.05	29.18	1.05	0.086	**4.54**	74	6	20	Sandy Loam/ Sandy Clay Loam
Chitedze	CP sole maize	5.86	1.00	1.72	**0.09**	20.83	1.05	0.101	1.96	64	10	26	Sandy Clay Loam
Chitedze	CA+ PP	6.13	1.71	2.96	0.15	7.62	1.52	0.084	4.53	64	8	28	Sandy Clay Loam
Chitala	PP + CA	6.01	1.69	2.87	0.16	114.08	1.64	0.124	3.26	64	8	28	Sandy Clay Loam
Chitala	CP sole maize	6.43	1.29	2.22	0.11	9.51	3.41	0.086	3.58	68	10	22	Sandy Clay Loam
Range		5.5–7.5	0.88–2.35	1.5–4.0	0.09–0.15	19.0–25.0	0.11–0.40	**2.0**	0.2–4.0				

Analysis conducted at the Chitedze Agricultural Research Station laboratory. Bold represents values outside the range.

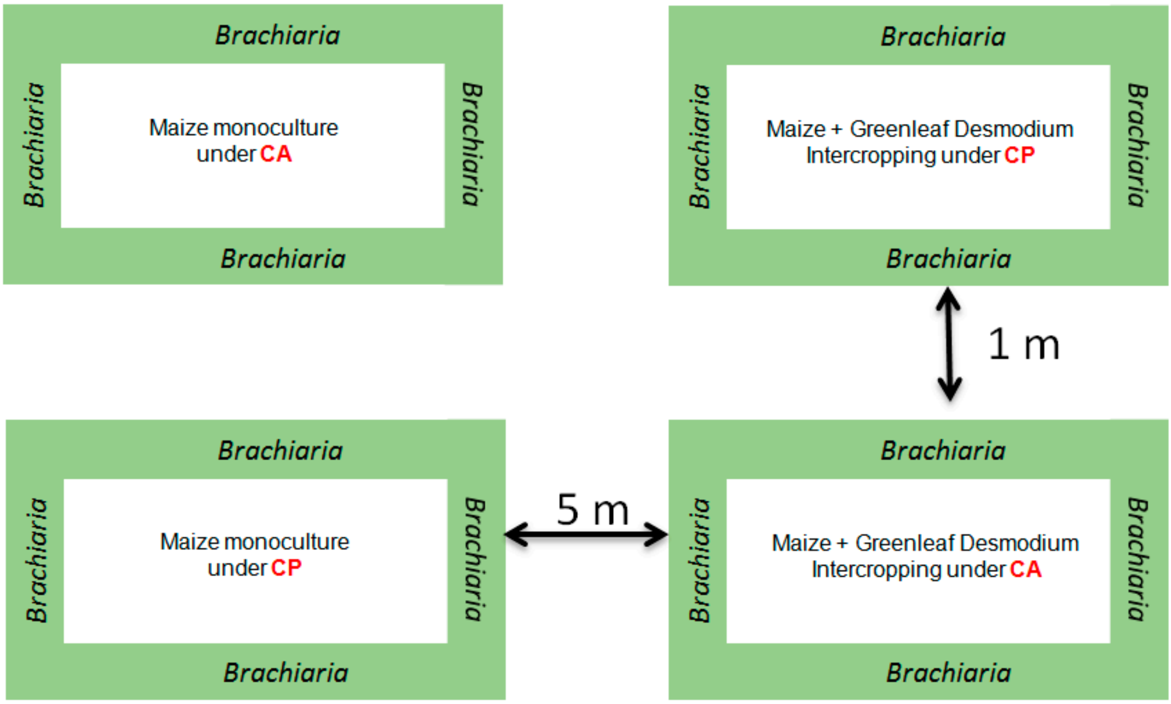

Figure 3. Schematic description of the plot layout. CA: Conservation agriculture; CP: Conventional practice.

2.3. Land Preparation

During the first year, the land was ploughed and harrowed in the conventional plots under dry conditions to achieve a fine soil tilth, ensuring good germination of small-seeded legumes such as *Desmodium*. The untilled CA-based plots were mulched with maize stalks at the recommended 2–3 t/ha [34]. The CP-based plots were not mulched to mimic the farmers' CP. In the second and third years, crop residues were removed in the CP plots as per the farmer's practice and retained in the CA plots.

2.4. Planting and Crop Management

Maize was used as a test crop and was sown on flat soil surfaces with a dibble stick and ridges in the CA and CP plots, respectively. The rows were spaced at 75 cm apart, with seeds sown at 25 cm apart within each row. Two maize seeds were initially sown and later thinned to one plant per planting station, two weeks after emergence, to maintain an optimum plant population of 53,000 per hectare [35]. The same plots and their respective treatments were consistently maintained for three years.

Two rows of *Brachiaria* were planted around the maize/*Desmodium* intercropping plots. *Desmodium intortum* was planted between the two rows of maize in all the intercropping plots at a spacing of 37.5 cm from the maize row to protect maize from outside *Striga* infestation (Figure 3). The seeds were mixed with dry sand in the ratio of one part of seeds to three parts of dry sand to ensure the uniform distribution of *Desmodium* within a row. The seeds were broadcasted into the shallow grooves at an average soil depth of 1 to 2 cm under adequate soil moisture conditions to enhance good germination [36].

2.5. Weed Management

At planting, glyphosate was applied in CA plots at a rate of 2.5 L ha^{-1} as a general spray, and careful superficial manual (hand pulling, where necessary light hoe) weeding was performed within the cropping season. Weeding in CP plots was carefully carried out at 3 and 5 weeks after planting (WAP) to avoid uprooting *Desmodium* intercrop plants. The missing gaps were filled using root splits/cuttings or vines to optimize the *Desmodium* plant population. *Desmodium* has very aggressive growth habits; if sown as an intercrop and left untrimmed, it can overshadow or smother the maize companion crop. Therefore, *Desmodium* was continuously trimmed until the maize crop reached knee height before it was left to cover the soil. This activity was performed at 3 and 6 WAP, as recommended by Khan et al. [36].

2.6. Data Collection

2.6.1. Maize Yield

Maize yield data was determined according to an area of 3 m × 3 m within each plot to avoid border effect errors. The fresh weights of the cobs at harvest were recorded from each quadrant. Composite samples from each treatment (about 5 cobs) were taken for dry cob weight, grain weight, and grain moisture at harvest. Samples were sundried, and grain moisture content was measured and adjusted to 13% using a handheld grain moisture meter (Dickey-John USA Grain Moisture Tester, *Minigac* GAC 2500_US, R. K. Enterprises, New Delhi, India) as stipulated in Lark et al. [37]. The grain moisture adjustment was performed to help standardise the yield performance of different treatments and eliminate experimental error sources due to differences in drying methods.

Plant height was recorded at harvest by recording the maize height of 10 plants per plot, from the ground level to the first split of the tassels.

2.6.2. *Striga* Infestation and Stemborer Damage

The *Striga* experiment was conducted at the Mbawa Research Station in the 2017–2018 and 2018–2019 maize growing seasons. *Striga*-infested plants were recorded in a 3 m × 3 m quadrant at 6, 8, and 10 WAP. The scale of 1–4 was used to score the severity of *Striga* infestation, where 1, 2.5, and 4 meant low, moderate, and high infestations, respectively [38].

The extent of stemborer damage to the maize plants was recorded at the Chitedze Research Station in the 2017–2018 and 2018–2019 maize growing seasons. The severity of the infestation was scored by visual observation of the damage attributed to the pest, using a 1–5 scale at the Mbawa Research Station in the 2017–2018 and 2018–2019 maize growing seasons. According to this prescribed scale, 1 = clean, with no visual infestation symptoms; 2 = very little damage; 3 = high level of damage, where plants show characteristic 'window-paned' and 'pin-holed' leaves and dead-hearts arising from stemborer larval feeding; 4 = severe damage, where almost 75 % of the plant is severely affected; and 5 = very severe damage, where total plant damage due to stem borer is visible [27,39].

2.6.3. *Striga* and *Desmodium* Mapping

Striga suitability analysis was performed using a GIS multicriteria decision-making approach. A literature review, expert opinions, and information collected in the field guided the variables to be incorporated in the *Striga* suitability analysis. The variables included annual mean rainfall, annual mean temperature, soil pH, soil organic concentration, and soil nitrogen and sand content. The raster datasets on each of these indicators were assembled, resampled to a resolution of 1 km, and processed from several sources for the Malawi region. The *Striga*-suitable areas were obtained by overlaying all the thematic layers in terms of weighted overlay methods, using the spatial analysis tool in ArcGIS 10.3 [40].

These layers were reclassified to a common suitability scale of 1 to 9, where class '9' represented the highest value. The evaluation scale was chosen following [41]. The reclassified layers were then weighted by assigning an equal percentage influence value. This is achieved by multiplying each raster cell's reclassified value by its layer weight and totaling the values to derive a suitability value. Both weight and rating values were assigned through expert knowledge and field observations. The output was compiled to produce a map indicating *Striga* suitability levels in Malawi.

In situ data retrieved from the Global Biodiversity Information Facility (GBIF: https://www.gbif.org/: accessed 2 November 2021) was used to develop ecological niche models of *D. uncinatum* (Silverleaf *Desmodium*) (n = 43) and *D. intortum* (Greenleaf *Desmodium*) (*n* = 36), which are the species favourable for the conventional and climate-smart PPT systems, respectively [27]. Presence records of the two species were combined with 19 bioclimatic variables to assess habitat suitability of the forage legume by using maximum entropy modelling (MaxEnt) in the MaxEnt tool package, version 3.4.0 k, which performs well for modelling presence-only data. This machine learning algorithm estimates a species distribution closest to uniform based on the environmental conditions at known occurrence sites [42]. The 19 bioclimatic layers contain grids of temperature and rainfall variables that interpolate observed data at a spatial resolution of 1 km. The layers were sourced from the Worldclim data repository (https://worldclim.org/: accessed 2 November 2021). The variance inflation factor method was applied to eliminate collinear variables [43]. This exercise was performed using R software's 'usdm' package [44,45]. Out of the 19 bioclimatic variables, 8 were considered for the modelling experiment. Response curves and jack-knife graphs were used to assess variable importance following [43].

Seventy percent of the 'presence only' data was used as training data, while 30% was used to validate the model [46,47]. The threshold independent area under the curve (AUC) of the receiver operating characteristic (ROC) was used to assess the accuracy of the model [48].

2.7. Focus Group Discussion

Focus group discussions (FGDs) were used to understand the socio-economic profiles of the targeted villages/communities, the main economic activities, crop and livestock production constraints, and how these constraints are tackled locally [49]. Farmers' perceptions of the technology's benefits and possible adoption challenges were investigated, and an emphasis was placed on maize production constraints. Further, the FGDs elicited information on the sources of agricultural extension information. Eight FGDs were conducted in four of the five project districts (i.e., two FGDs in each district), where PPT was being validated for scaling-up. The four districts covered were Lilongwe, Salima, Nkhotakota, and Mzimba. The FGDs each constituted a group of about 9–25 key informants of both genders. Informants were assembled in a central place in a village. These key informants came from different villages. A prepared checklist was used to guide the discussions, which an economist moderated. An interpreter who was fluent in the local language facilitated the interview. Following the PPT demonstration, the host farmers were asked to enumerate some of the potential benefits they had experienced in the last season when they hosted the demonstrations.

2.8. Data Analysis

The data were subjected to the general analysis of variance (ANOVA) model using Genstat (Version 15.1, VSN International Ltd., Hemel Hempstead, UK). Statistical comparisons of the treatment means at a 5% probability level were conducted using the least significant differences (LSD).

3. Results

3.1. Effect on Grain Yields and Number of Cobs

Overall, there were significant decreases over the years ($p < 0.001$) and between the various sites ($p < 0.001$), and the interactions between the years and the sites were also significant ($p < 0.001$). Overall, the treatment effect was not significant; however, the interaction between the sites and the treatment was marginally significant ($p = 0.045$). The interaction between treatment and year was not significant, and the combined interaction between treatment, year, and site were also not significant ($p = 0.082$).

3.2. Effect of Push–Pull Technology on Grain Yields at Chitedze, Mbawa, and Chitala Research Stations

In Chitedze, the treatments had a significant effect ($p < 0.01$) on the grain yield. In 2016–2017, maize grain yields were significantly higher in CP by 1001, 1967, and 1691 kg than CP–PP, CA, and CA–PP, respectively. The yield in CP–PP was significantly higher by 690 kg and 966 kg than those in CA and CA–PP, respectively. In 2017–2018, maize grain yield was significantly higher in CA than CP, CA–PP, and CP–PP by 1031, 1975, and 2761 kg, respectively. There was also a significant difference between CP on the one hand and CA–PP and CP–PP on the other. In 2018–19, CP treatments again recorded the highest yields, but no significant differences were found between the other treatments.

In Mbawa, there was a significant seasonal effect ($p < 0.001$) on the grain yield. Season 2016–2017 recorded the highest grain yield. In 2016–2017, sole maize treatments in CP and CA had higher grain yields by 2376 and 2316 kg than in CA–PP. However, no significant differences were found between CA, CP, and CP–PP. In 2017–2018, no significant differences were found between the treatments. In the 2018–2019 season, CP–PP recorded significantly higher maize grain yield by 1227 kg and 1269 kg than CA and CP and was not significantly different from CA–PP (Table 2).

Table 2. Effects of treatments on maize grain yield (kg ha^{-1}) research station in the 2016–2017, 2017–2018, and 2018–2019 growing seasons.

Treatments	**Growing Seasons** 2016–2017	2017–2018	2018–2019	**Treatments Effect**
Chitedze Research Station				
CA—PP	2584 ^{c}	2229 ^{c}	3121 ^{b}	2645
CA sole maize	2308 ^{c}	4204 ^{a}	3811 ^{b}	3441
CP—PP	3274 ^{b}	1443 ^{c}	3457 ^{b}	2725
CP sole maize	4275 ^{a}	3173 ^{b}	5260 ^{a}	4236
Seasonal effects	3110 ^{B}	2762 ^{B}	3912 ^{A}	
LSD Seasons (Y): 989.1 * LSD Treatments (T): 856.6 ** LSD T × Y: 1713.2 ns				
Mbawa research station				
CA—PP	3300 ^{cbd}	1948 ^{a}	3982 ^{ab}	3077
CA sole maize	5616 ^{a}	2071 ^{a}	3395 ^{bc}	3694
CP—PP	4859 ^{da}	3046 ^{a}	4622 ^{a}	4176
CP sole maize	5676 ^{a}	2322 ^{a}	3353 ^{bc}	3784
Seasonal effects	4863 ^{A}	2347 ^{B}	3838 ^{C}	
LSD Seasons (Y): 1007.4 *** LSD Treatments (T): 1163.2 * LSD Y × T: 2014.8 ns				
Chitala research station				
CA—PP	8379 ^{a}	7794 ^{a}	3299 ^{a}	6491
CA sole maize	8569 ^{a}	6595 ^{ba}	4384 ^{ab}	6516
CP—PP	6697 ^{ba}	7009 ^{a}	3373 ^{a}	5693
CP sole maize	8297 ^{a}	4320 ^{cb}	4135 ^{a}	5584
Seasonal effects	7986 ^{A}	6429 ^{B}	3798 ^{C}	
LSD Seasons (Y): 1221.8 ***, LSD Treatments (T): 1410.8 ns, LSD T × Y: 2343.6 ns				

Values with the same letter under the same parameter are not significantly different at * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant at $p < 0.05$; LSD, least significant difference; CA—PP, push–pull system under conservation agriculture (CA)—maize/*Desmodium* intercropping; CA sole maize, sole maize cropping under CA; CP—PP, push–pull system under CP—maize/*Desmodium* intercropping; and CP sole maize, sole maize cropping under CP. Values with letters in the uppercase compare the means across the columns.

In Chitala, there was a significant seasonal effect on the grain yield ($p < 0.05$). No statistical differences were detected between the treatments in 2016–2017 and 2018–2019. However, in 2017–2018 maize grain yields in CP were significantly lower by 3474, 2689, and 2275 kg than in CA–PP, CP–PP, and CA (Table 2).

3.3. Effect of Push–Pull Technology on the Number of Maize Cobs at Chitedze, Mbawa and Chitala Research Stations

In Chitedze, there was a significant effect ($p < 0.001$) of the season and the treatments on the number of maize cobs harvested (Table 3). In 2016–2017, CP and CP–PP plots had significantly higher numbers of maize cobs by 11.7, 15.7, and 8.7, 12.7 than CA and CA–PP, respectively. However, in 2017–2018, CP, CA, and CP–PP had a significantly higher number of cobs, respectively, by 12.6, 12.3, and 9.0 than CA–PP. In the 2018–2019 season, CP recorded a significantly higher number of cobs by 4.7, 7.7, and 10.0 than CP–PP, CA–PP, and CA (Table 3).

Table 3. Effects of growing seasons and treatments on the mean number of maize cobs harvested (number/plot) between the 2016–2017 and 2018–2019 seasons.

	Growing Seasons			
Treatments	**2016–2017**	**2017–2018**	**2018–2019**	**Treatments Effect**
Chitedze Research Station				
CA—PP	32.3 [a]	19.7 [b]	28.6 [b]	26.6
CA sole maize	28.3 [a]	32.0 [a]	26.3 [b]	28.8
CP—PP	41.0 [b]	28.7 [a]	31.6 [b]	33.7
CP sole maize	44.0 [b]	32.3 [a]	36.3 [a]	37.5
Seasonal effects	36.4 [A]	28.2 [B]	30.1 [B]	
LSD Seasons (Y): 5.5 **, LSD Treatments (T): 4.6 **, LSD Y × T: 9.6 ns				
Mbawa Research Station				
CA—PP	36.3 [a]	18.0 [c]	22.3 [dc]	25.5
CA sole maize	39.3 [b]	18.3 [c]	21.0 [c]	26.2
CP—PP	40.6 [a]	30.7 [a]	25.3 [a]	32.0
CP sole maize	41.3 [a]	25.3 [b]	17.9 [b]	26.7
Seasonal effects	39.4 [A]	21.8 [C]	21.6 [B]	
LSD Seasons (Y): 2.68 ***, LSD Treatments (T): 3.09 *** LSD Y × T: 5.36 *				
Chitala Research Station				
CA—PP	41.7 [a]	67.0 [a]	34.7 [b]	47.8
CA sole maize	33.0 [b]	66.7 [a]	34.7 [b]	44.8
CP—PP	40.0 [a]	64.3 [a]	34.3 [b]	46.2
CP sole maize	46.7 [a]	34.3 [b]	41.3 [a]	50.3
Seasonal effects	40.3 [B]	65.2 [A]	36.2 [C]	
LSD Seasons (Y): 8.5 ***, LSD Treatments (T): 9.81 * LSD Y × T: 17.0 ns				

Values with the same letter under the same parameter are not significantly different at * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant at $p < 0.05$; LSD, least significant difference; CA—PP, push–pull system under conservation agriculture (CA)—maize/*Desmodium* intercropping; CA sole maize, sole maize cropping under CA; CP—PP, push–pull system under CP—maize/*Desmodium* intercropping; and CP sole maize, sole maize cropping under CP. Values with letters in the uppercase compare the means across the columns.

In Mbawa, the number of maize cobs harvested was significantly affected by the seasons and the treatments. The 2017–2018 season recorded a significantly higher maize cobs than the other two seasons (Table 4). In 2016–2017, CP, CP–PP, and CA showed higher numbers of cobs by 5.0, 4.3, and 3 than CA–PP. In 2017–2018, CP–PP recorded a higher number of cobs by 5.4, 12.4, and 12.7 than CP, CA, and CA–PP. In 2018–2019, CP–PP recorded a higher number of cobs by 3.0, 4.3, and 7.4 than CA–PP, CA, and CP, respectively. There were significant differences between CA and CP but no differences between CA–PP and CA (Table 4).

Table 4. Effects of growing seasons and treatments on the mean number of stemborer exit holes at Chitedze Research Station between the 2016–2017 and 2017–2018 seasons.

	Growing Seasons			Growing Seasons		
	2016–2017	**2017–2018**	**Treatments Effect**	**2016–2017**	**2017–2018**	**Treatments Effect**
Treatments	**Number of Stemborer Exit Holes**		**Season Mean**	**Stemborer Severity**		**Season Mean**
CA—PP	3.10 [c]	0.73 [b]	1.92	2.0 [a]	1.3 [b]	1.7
CA sole maize	3.13 [c]	2.25 [a]	2.69	2.3 [ab]	1.7 [b]	2.0
CP—PP	3.79 [b]	1.01 [b]	2.40	3.3 [c]	3.0 [a]	3.2
CP sole maize	4.23 [a]	2.20 [a]	3.22	3.6 [c]	2.7 [a]	3.1
Seasonal effects	3.56 [A]	1.56 [B]		2.8 [A]	2.2 [B]	

LSD Seasons (Y): 0.307 ***, LSD Treatments (T): 0.409 ***, LSD Y × T: 0.614 ns
LSD Seasons (Y): 0.819 ns, LSD Treatments (T): 1.158 **, LSD, Y × T: 1.639 ns

Values with the same letter under the same parameter are not significantly different at * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant at $p < 0.05$; LSD, least significant difference; CA—PP, push–pull system under conservation agriculture (CA)—maize/*Desmodium* intercropping; CA sole maize, sole maize cropping under CA; CP—PP, push–pull system under conventional practice (CP)—maize/*Desmodium* intercropping; and CP sole maize, sole maize cropping under CP. Values with letters in uppercase compare the means across the columns.

In Chitala, the season and the treatment significantly affected the number of cobs harvested. The 2017–2018 season had an increased number of maize cobs harvested. In 2016–2017, CP showed a significantly higher number of cobs (by 13.7) than CA, while in 2017–2018, CA, CP–PP, and CA–PP recorded a higher number of cobs, respectively, by 0.3, 2.7, and 32.7 than CP. However, in 2018–2019, the number of cobs harvested under CP was higher by 7.0, 6.6, and 6.6 than CP–PP, CA, and CA–PP (Table 4).

3.4. Effect on the Damage Level: Number of Stemborer Exit Holes

The season and the treatment significantly affected the number of exit holes. During the 2016–2017 growing season, CP had more exit holes than CP–PP, CA, and CA–PP (respectively by 0.44, 1.10, and 1.13). There were significant differences between CP–PP on the one hand and CA and CA–PP on the other, but no significant differences were recorded between CA and CA–PP. Stemborer severity in CP was significantly higher by 1.3 and 1.6 than CA and CA–PP, respectively. There were also significant differences between CP, CA and CP–PP. However, there were no significant differences between CP and CP–PP and between CA and CA–PP (Table 4).

In the 2017–2018 season, CA–PP and CP–PP recorded significantly fewer numbers of stemborer exit holes than (CA–PP: 1.52 and 1.47 for CA and CP, respectively, and CP–PP: 1.24 and 1.19 for CA and CP, respectively). Stemborer severity showed a similar trend to that of the previous year (Table 4).

3.5. Striga Severity and Number of Plants Affected by Striga

Striga severity was significantly affected by the seasons and treatments. The 2018–2019 season recorded significantly higher *Striga* severity than 2017–2018 (Table 5). In 2017–2018 the *Striga* severity was significantly higher by 0.6, 0.7, and 1 than CP–PP–CA and CA–PP. The number of plants affected by *Striga* reflected a similar trend as the severity score.

Table 5. The effects of cropping systems on the mean severity of *Striga* on the maize plants at Mbawa Research Station in the 2017–2018 and 2018–2019 growing seasons.

	Growing Seasons			
	2017–2018	2018–2019	2017–2018	2018–2019
Treatments	*Striga* Severity		Number of Affected Plants	
CA—PP	1.0 ^{bc}	1.3 ^{b}	0.67 ^{b}	6.0 ^{d}
CA sole maize	1.3 ^{b}	1.6 ^{b}	0.12 ^{bc}	8.3 ^{c}
CP—PP	1.4 ^{b}	3.6 ^{a}	0.68 ^{b}	18.0 ^{b}
CP sole maize	2.0 ^{a}	3.3 ^{a}	2.67 ^{a}	24.3 ^{a}
Seasonal effects	1.4 ^{A}	2.5 ^{B}	1.00 ^{A}	14.2 ^{B}
LSD Seasons (Y): 0.569 ***, LSD Treatments (T): 0.605 ** LSD Y × T: 1.138 *			LSD Seasons (Y): 2.635 ***, LSD Treatments (T):0.989 *** LSD Y × T: 5.269 **	

Severity was rated from 1–4, where 1 = low infestation, 2.5 = moderate infestation, and 4 = highest infestation. The mean number of maize plants (plants/9 m^2) affected by *Striga* as influenced by cropping systems at Mbawa Research Station in the 2017–2018 and 2018–2019 growing seasons. Values with the same letter under the same parameter are not significantly different at * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant at $p < 0.05$; LSD, least significant difference; CA—PP, push–pull system under conservation agriculture (CA)—maize/*Desmodium* intercropping; CA sole maize, sole maize cropping under CA; CP—PP, push–pull system under conventional practice (CP)—maize/*Desmodium* intercropping; and CP sole maize, sole maize cropping under CP. Values with letters in uppercase compare the means across the columns.

The 2018–2019 season had the highest infestation of *Striga* (Table 5). CP–PP and CP recorded a higher severity than CA (2.0 and 1.7) and CA–PP (2.3 and 2.0), respectively. The number of plants affected by *Striga* also reflected a similar trend as the severity score (Table 5).

3.6. Effects of Growing Seasons and Treatments on Maize Plant Height (cm) at Chitedze Research Station between the 2016–2017 and 2017–2018 Seasons

Seasons and treatments significantly affected maize plant height. In 2016–2017, CP recorded significantly shorter maize plants by 14.1, 11.6, and 5.8 cm than CP–PP, CA, and CA–PP, respectively (Table 6). There were no significant differences in plant height between CP–PP, CA, and CA–PP. Similarly, in 2017–2018, CP also recorded significantly shorter maize plants by 19.2, 23.9, and 24.9 cm than CP–PP, CA, and CA–PP, respectively (Table 6).

Table 6. Effects of growing seasons and treatments on maize plant height (cm) at Chitedze Research Station between the 2016–2017 and 2017–2018 seasons.

	Growing Seasons		
Treatments	2016–2017	2017–2018	Treatments Effect
	Plant Height (cm)		
CA—PP	154.9 ^{a}	137.2 ^{a}	146.1
CA sole maize	160.7 ^{a}	136.2 ^{a}	148.5
CP—PP	163.2 ^{a}	131.5 ^{a}	147.4
CP sole maize	149.1 ^{b}	112.3 ^{b}	130.7
Seasonal effects	157.0 ^{A}	129.2 ^{B}	
LSD Seasons (Y): 9.21 ***, LSD Treatments (T): 12.23 ** LSD Y × T: 18.35 ns			

Values with the same letter under the same parameter are not significantly different at * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant at $p < 0.05$; LSD, least significant difference; CA—PP, push–pull system under Conservation Agriculture (CA)—maize/*Desmodium* intercropping; CA sole maize, sole maize cropping under CA; CP—PP, push–pull system under conventional practice (CP)—maize/*Desmodium* intercropping; and CP sole maize, sole maize cropping under CP. Values with letters in the uppercase compare the means across the columns.

3.7. *Striga* Mapping

The output map showed regions with high to low suitability for *Striga* occurrence in the whole country (Figure 4). The model predicted a very high *Striga asiatica* suitability in areas around the Mbawa and Chitedze Research Stations, whereas it was moderate to low in the Chitala Research Station area.

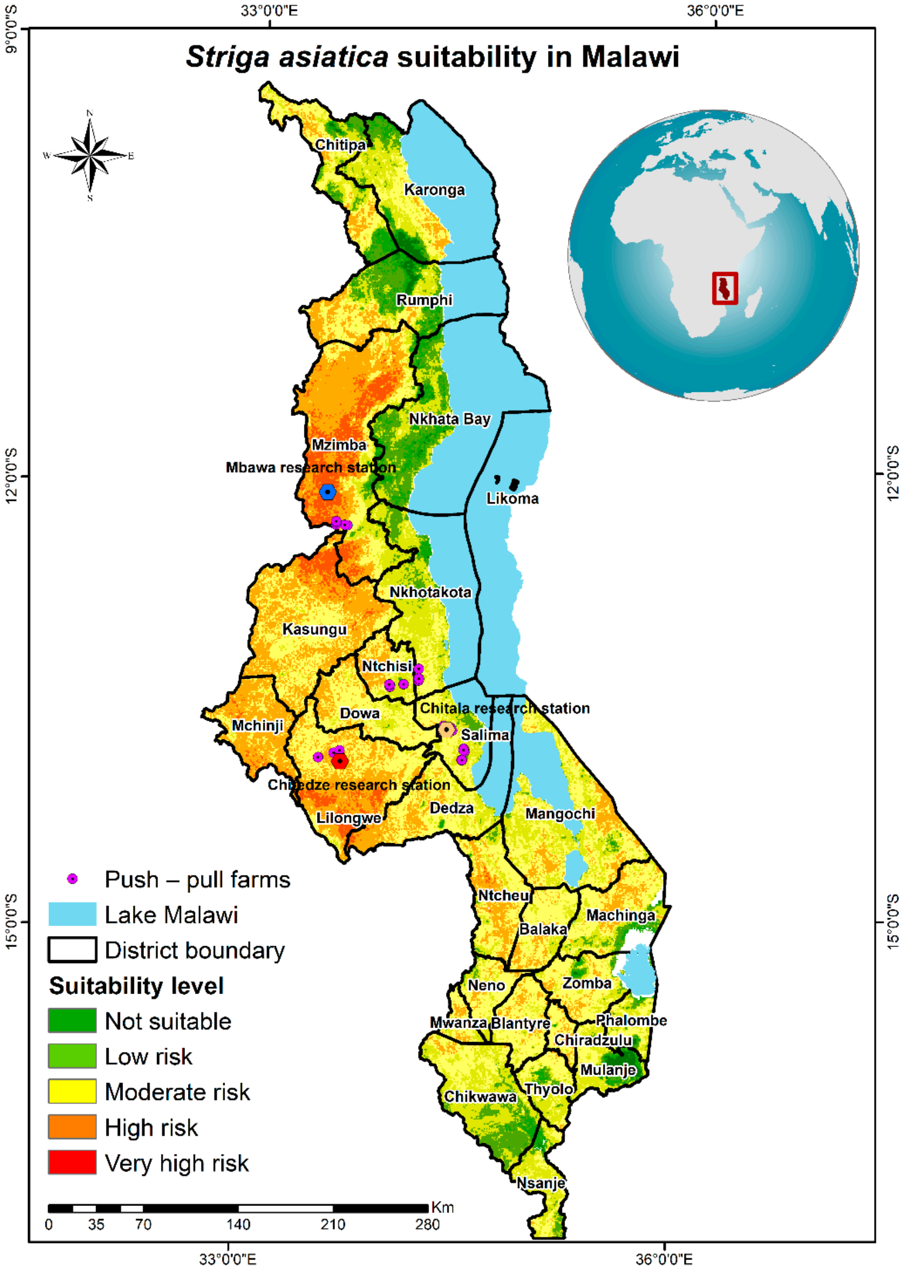

Figure 4. Predictive occurrence of *Striga* infestation in Malawi.

3.8. *Desmodium* Climate Suitability Model

The AUC values were all higher than 0.5, indicating an optimal occurrence area in all the species (Figure 5). This shows that the model successfully predicted the suitable habitat area for the two *Desmodium* species.

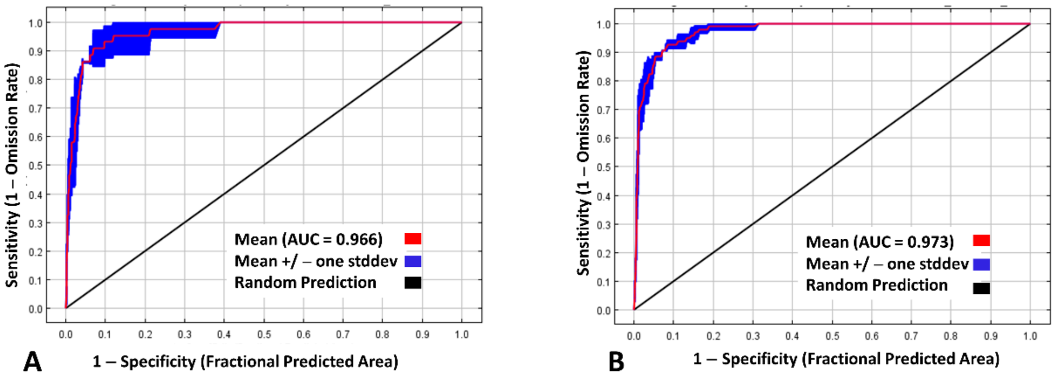

Figure 5. Receiver operating characteristic with the area under curve (AUC) graphs of the ensemble model outputs of predicting (**A**) Silverleaf and (**B**) Greenleaf *Desmodium*.

The jack-knife test demonstrated that precipitation of the warmest quarter (Bio_18) is the most important variable in determining the suitability of the two *Desmodium* species (Figure 6).

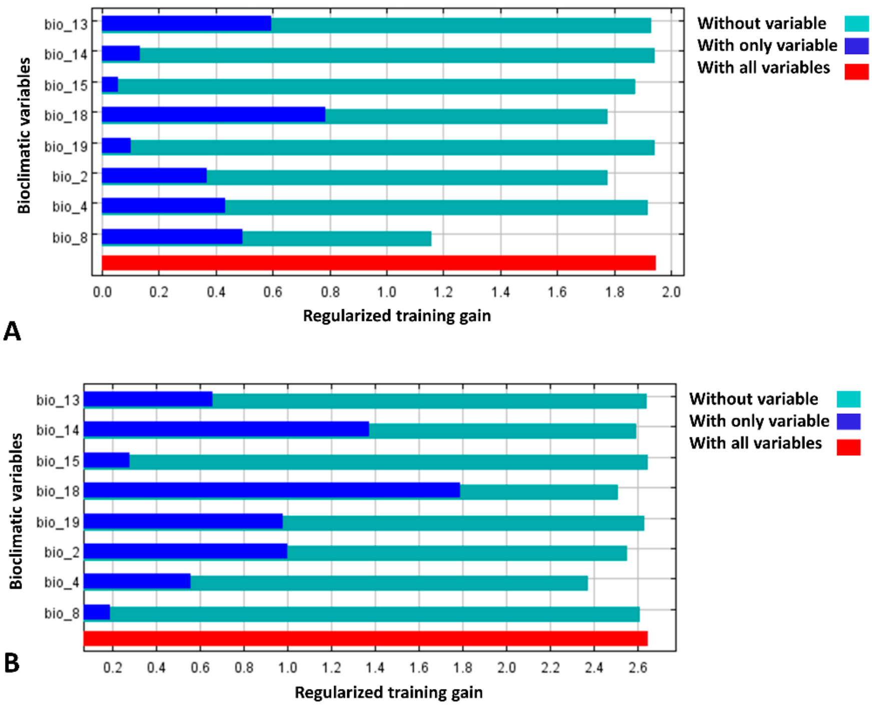

Figure 6. The relative importance of bioclimatic variables for predicting the climate suitability of (**A**) Silverleaf and (**B**) Greenleaf *Desmodium* based on the jack-knife test.

The response of *Desmodium* performance to the four most important bioclimatic variables is illustrated. The response curves of the four variables in the Silverleaf *Desmodium* model (Figure 7) indicated that Silverleaf *Desmodium* performs optimally at the precipitation of 400–600 mm in the warmest quarter (Figure 7A) and up to 1200 mm in the wettest month (Figure 7C). The forage legume thrives in a mean temperature of 20 °C in the wettest quarter (Figure 7B) and a mean diurnal temperature range of 6–10 °C (Figure 7D).

The response curves of the four variables in the Greenleaf *Desmodium* model (Figure 8) indicated that Greenleaf *Desmodium* performs optimally at the precipitation of 400–1400 mm in the warmest quarter (Figure 8A) and between 20–160 mm in the driest month (Figure 8C). It thrives well even with a high temperature seasonality (Figure 8B) and a mean diurnal temperature range of 6–8 °C (Figure 8D).

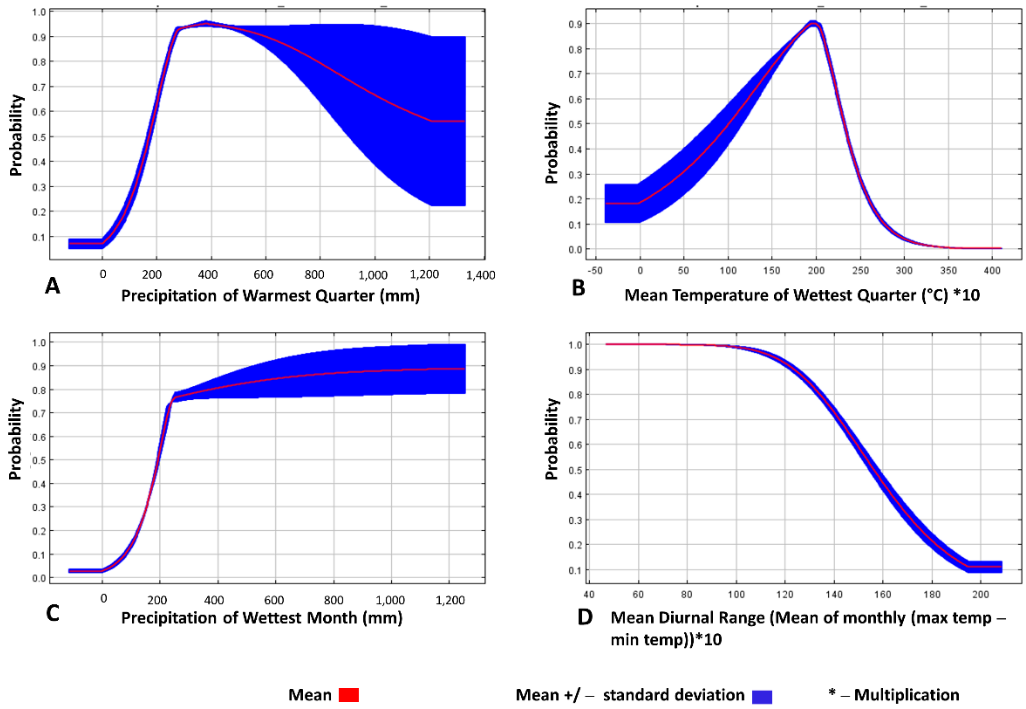

Figure 7. Response curves for the selected bioclimatic variables to predict suitable habitats for Silverleaf *Desmodium* in Malawi. The star (*) means multiplication.

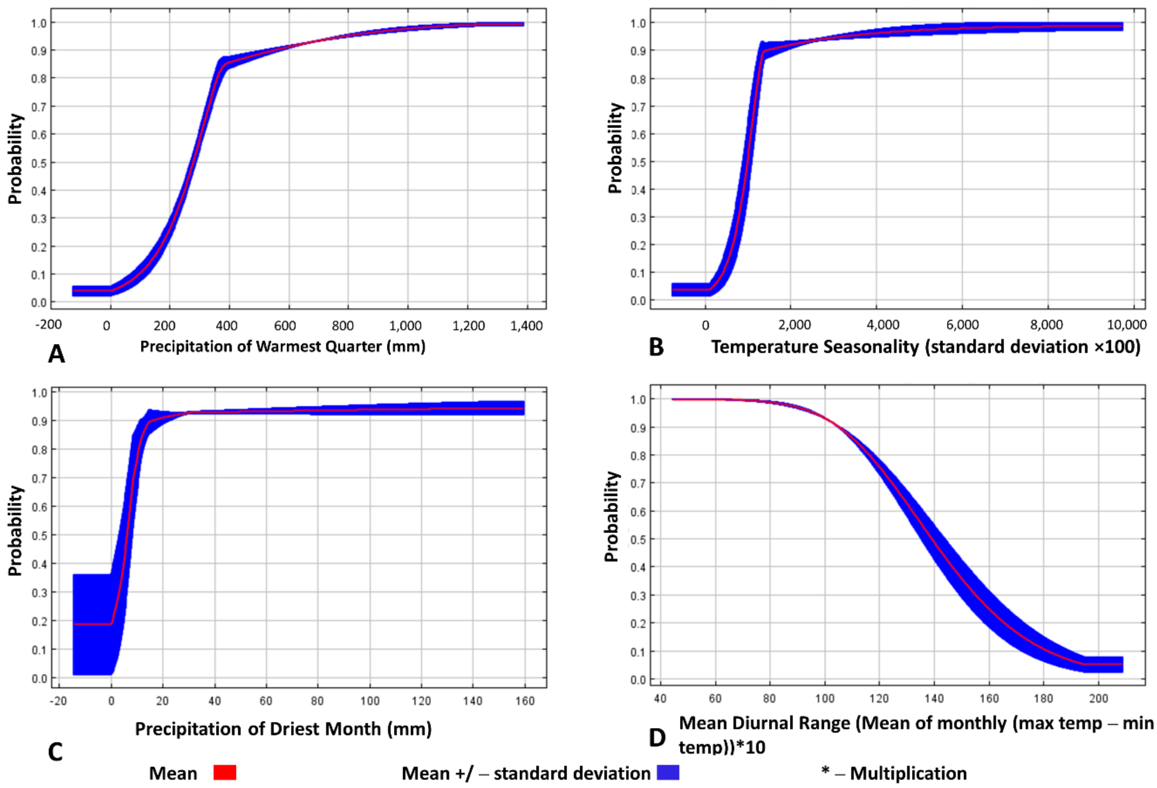

Figure 8. Response curves for the selected bioclimatic variables to predict suitable habitats for Greenleaf *Desmodium* in Malawi. The star (*) means multiplication.

A comparison of the two models indicated that Silverleaf *Desmodium* generally has higher suitability than Greenleaf *Desmodium* across all the districts in Malawi (Figure 9). The suitability of Greenleaf *Desmodium* used in this study in the target districts was found to be very low (Figure 9).

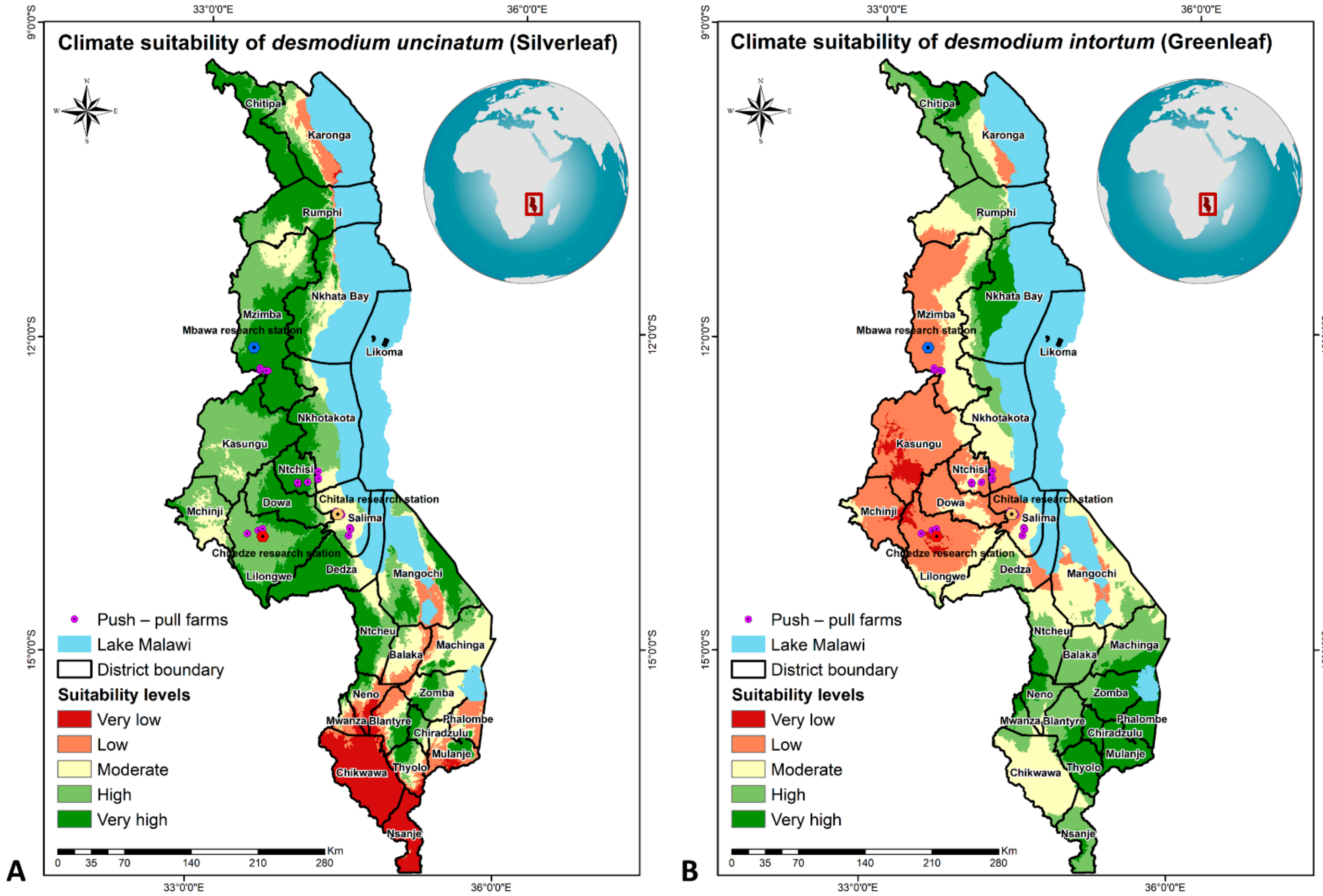

Figure 9. Predicted climate suitability of (**A**) Silverleaf and (**B**) Greenleaf *Desmodium* in Malawi.

3.9. Focus Group Discussions

After introducing PPT, farmers showed much enthusiasm in taking up the technology since they noticed that it could significantly reduce *Striga* weed and stemborer pests by up to 70%. They also attested that they had seen a significant increase in maize yield (Table 7). However, the cost of labour in terms of ploughing, planting, weeding, harvesting, and threshing was higher in PPT-based treatments.

Table 7. Profitability analysis of CA–PP technology in Malawi (per hectare of land) during the baseline survey.

District	Ploughing and Planting (Person-Days)	Weeding (Person-Days)	Harvesting (Person-Days)	Threshing (Person-Days)	Yield (kg/ha)
With Conservation Agriculture and Push–Pull Technology (CA—PP)					
Lilongwe	24	16	12	12	2400
Salima	56	24	48	14	6400
Nkhotakota	50	20	24	18	2880
Mzimba	44	21	42	56	4000
Mean	44	20	32	25	3920
Without Conservation Agriculture and Push–Pull Technology (CA—PP)					
Lilongwe	8	12	8	6	1200
Salima	36	18	32	8	3600
Nkhotakota	28	12	18	14	1920
Mzimba	22	12	35	42	3200
Mean	24	14	23	18	2480

4. Discussion

Despite deficient soils and erratic rainfall patterns, the expected agronomic benefits in yield, pest management, and plant features were achieved under CA and CP. The PPT performed well in Chitedze in the 2016–2017 season, in Mbawa in the 2017–2018 and 2018–2019 seasons, and in Chitala in 2016–2017 and 2017–2018 seasons. The lack of consistency in performance can be linked to the variabilities between the sites [1,2]. Crop performance in terms of yield was related to soil physicochemical properties (Table 8). Soil analysis results showed an excess of potassium in all samples. Mbawa soils are acidic and deficient in nutrients, including nitrogen, essential for maize growth. Chitedze soils are also acidic and deficient in nitrogen and phosphorus, and their pH is moderately acidic. Chitala soils are less acidic than others, often with an excess of phosphorus. Areas with high deficiency seemed more favourable for sole maize due to interspecific competition between maize, *Desmodium*, and *Brachiaria*. PPT seemed to be more compatible with CP in low-fertility soils.

Table 8. Correlation matrix between maize yield and physicochemical properties of the soils.

Years	Correlation Coefficient/*p* Value	pH	OC	OM	N	P	K	Ca	Mg	Clay	Silt	Rainfall
2017	R	0.303	0.175	0.160	0.217	0.632	0.524	0.426	0.555	−0.050	0.145	0.038
	p value	0.338	0.587	0.619	0.498	0.028	0.080	0.167	0.061	0.877	0.654	0.462
2018	R	0.637	0.537	0.530	0.542	0.337	0.763	0.065	0.737	0.239	0.433	0.546
	p value	0.026	0.072	0.076	0.069	0.283	0.004	0.842	0.006	0.454	0.160	0.290
2019	R	−0.026	−0.178	−0.181	−0.153	0.041	−0.128	0.205	−0.068	−0.037	0.143	0.064
	p value	0.937	0.580	0.574	0.635	0.899	0.692	0.523	0.834	0.909	0.657	0.750
Combined	R	0.344	0.243	0.234	0.263	0.368	0.463	0.208	0.472	0.064	0.228	0.076
	p value	0.040	0.154	0.169	0.121	0.027	0.004	0.223	0.004	0.712	0.181	0.255

Desmodium is a perennial plant that expands its root system in subsequent seasons [50]. CP supports ploughing, and the disturbance caused to the roots prevents competition for nutrients between maize and the companion plants (*Desmodium* and *Brachiaria*). PPT was only compatible with CA in Chitala, where soil nutrients were balanced. Results on grain yield and the number of cobs in that region testified to the agronomic performance of PPT under CA. In addition to these variabilities, the rainfall pattern may interfere with a crop's agronomic performance [51]. Seasons 2016–2017 and 2018–2019 had better rains than 2017–2018, except in Chitala, where the 2018–2019 season was not very impressive.

Observation of the numbers of exit holes found at Chitedze indicated that in 2016–2017, PPT and sole maize under CA had the lowest numbers. In 2017–2018, PPT under

CA and CP had the lowest exit holes. These results confirm previous findings of the superiority of PPT over convention practice in reducing lepidopteran pests, as described by Midega et al. [24], Hailu et al. [27], and Ndayisaba et al. [52]. These findings imply that maize under PPT produces better yields and has less ear rot, and hence fewer chances of Aflatoxin contamination, as reflected in the severity scores [53]. Both PPT and CA promote the presence of natural enemies, which support a more efficient control of the pest in subsequent seasons. In that regard, a spillover effect in adjacent control plots can be envisaged; hence, agronomic attributes in terms of plant vigour and height are the discriminating factors between treatments.

Both PPT and CA are soil-fertility-increasing technologies. CA is designed to increase biological diversity, reduce runoff and erosion, improve soil organic carbon, and improve crop yield [54–56]. Likewise, PPT improves soil moisture and nitrogen fixation, and *Desmodium* suppresses *Striga* through root exudates, mainly Isoschaftoside, a C-glycosylflavonoid, leading to suicidal germination of *Striga* seeds [57]. This has been confirmed in many earlier studies [52,58,59]. Additional attributes of PPT can be observed in Chitedze, whereby PPT maize plants in CP (2016–2017) and PPT maize plants under CA 2017–2018 were taller than the plants in the other treatments. It can be concluded that the application of PPT or CA contributes to a drastic reduction in *Striga* through soil fertility improvement.

Desmodium Greenleaf has very low suitability in the target sites. *Desmodium* Greenleaf originates from South America and requires neutral soils (pH < 7) [60]. Its optimal temperature ranges between 25 and 30 °C, and it performs better between 500 and 2500 m in the tropics where annual rainfall is above 900 mm and up to 3000 mm [60]. In that regard, *Desmodium* Silverleaf showed a much higher coverage and suitability in the country.

PPT is a sustainable and low-input production system that relies on household labour for ploughing, planting, weeding, harvesting, and threshing. PPT does not require external inputs such as chemical pesticides to reduce incidences of stemborer and *Striga* in maize. Farmers involved in the FGDs reported increased productivity between 45–50% and improved arthropod abundance, soil biota and soil organic matter, and overall environmental health. Recently, PPT was found to control FAW, a serious invasive pest of cereal crops in Africa [24,27]. Therefore, dissemination and outreach campaigns need to emphasize the multiple benefits of the technology, including the use of *Brachiaria* and *Desmodium* and fodder crops [61,62].

The FGDs showed that farmers considered PPT as a yield-increasing technology. However, the initial establishment and planting of PPT requires ploughing and harrowing the land to a fine tilth for the sowing of *Desmodium* seeds and the general layout of the plot. Several studies have demonstrated that the cost of the initial establishment might be high, but it is reduced over time.

5. Conclusions

This study is the first to investigate PPT's performance in various agroecological zones in Malawi under two farming practices. The study confirmed the classical benefits of technology in terms of stemborer and *Striga* control. However, PPT was more compatible with CP in low-soil-fertility areas, probably due to below-ground competition under CA. The combination of PPT and CA can only occur in areas of moderate soil fertility. Root pruning is therefore compulsory to avoid plant stunting in subsequent seasons. The combination of PPT and CA was very effective in controlling *Striga*. *Desmodium* Silverleaf is more suitable in Malawi than Greenleaf is. While further research is needed to identify indigenous *Desmodium*, the current study supports the release of the technology in Malawi. *Desmodium* and *Brachiaria* as animal fodder can offer a comparative advantage for adopting the technology.

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