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Original article

Measuring the ecological preference for growth of 150 of the most influential weeds in weed community structure associated with agronomic and horticultural crops

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A B S T R A C T

The phytosociological researches which intent for studying the performance of weeds and the structure of weed assemblages associated with different crops derives their importance mainly from the adverse effect of weeds on crop productivity. Consequently, it is worth questioning about the ecological preferences of the weed growth in response to three main drivers for weed community structure associated with agronomic, and horticultural crops: crop diversification, crop seasonality, and soil type. A study area was selected comprising farmland of Nile Delta and its adjoining east and west territories, Egypt. A total of 555 species were recorded in 30 agroecosystems monitored and depending on species frequency/abundance values, 150 species were designated as the most influential weeds in weed community structure associated with agronomic and horticultural crops. The ecological preference of species for crop seasonality was evident through the results of Agglomerative hierarchical clustering. Three weed assemblage groups (WAG) identified: WAG A associated with winter agronomic crops, WAG B associated with summer agronomic crops, and WAG C associated with perennial agronomic crops and horticultural crops (orchards). Their diversity evaluated at different levels. The growth preference of the 150 species which were assigned as most influential weeds was gauged in response to the three environmental variables. 61 species were faithful to WAG A, 45 to WAG B, and 44 to WAG C. Concerning crop diversification, 34-species were significantly affected and scored coefficient of variation $\geq$ 100%. As for soil type, indicator species analysis revealed that 66-species show growth preference in fine grained soil while 84-species prefer coarse grained soil. In the three vegetation units (WAG A – C), 12 within-group associations (alliances) were specified of less-common (differential) species. The record of these alliances match to a specific environmental condition (ecological niche) and in them 29 strong indicators are identified. Redundancy analysis was used to extract and summarize the variation in species records in the response matrix (species vs. sites) that can be explained by the three different types of growth preference (explanatory variables), and the partial linear effect of them was evaluated by variation partitioning.

1. Introduction

The adverse impact of weeds on crop productivity is a matter of discussion in weed science researches (Ryan et al., 2009; and Torun, and Uygur, 2018). Several researchers concluded that the harmful effect of weeds on crop productivity is enhanced by presence of invasive species (Thebaud et al., 1996; Reichard, and Hamilton, 1997; Kolar and Lodge, 2001). These studies also revealed that invasive species appear to have specific traits or specific combinations of traits that allow them to outcompete not only the native species but crops as well. The high ecological competence, phenotype plasticity, fast growth, high dispersal ability, and fast renewal capability after local fire events are some of the most common features of invasive species. The increasing harmful effect of weeds on crop yield in combination to the increase of food requirements, encouraged ecologists to pay further attention in order to introduce (suggest) methods of solving this snag. Several models have been suggested describing weed–crop competition and the relationship between weed abundance/

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crop yield. These models in addition to being useful for predicting yield loss and developing management guidelines (Zimdahl, 2004) are also valuable of characterizing the effects of weeds on crop yields under different management systems, and evaluating the effectiveness of suites of tactics applied together (Bastiaans et al., 1997, 2008; Van Ittersum et al., 2003; Nesser et al., 2004). However, for the implementation of such programs to be successful an accurate knowledge is needed as far as diversity, distribution, frequency, abundance, and phenology of weed species and communities is concerned (Frick and Thomas, 1992; Ghersa and Holt, 1995). Moreover, such kind of data might also be crucial for understanding weed communities and for creating a higher biodiversity in arable land (Andreasen and Skovgaard, 2009). Despite the fact that weed assemblages associated with either agronomic or horticultural crops were the object of several phytosociological studies (Amer and Abd El-Ghani, 1990; Menalled et al., 2001; Mashaly et al., 2002; Shaltout et al., 2015; Ahmad et al., 2016; Begum and Ahmad, 2016; Mahgoub, 2017, 2019a, 2019b), this topic has not been yet adequately addressed. Present study aims to the interpretation of ecological preference (as far as growth under different microenvironmental conditions is concerned) of 150 weed species evaluated as the most influential in the structure of weed communities associated with agronomic and horticultural crops. We hope this attempt will be useful in developing sustainable long term weed management strategy.

Also, the cultivation of non-traditional crops especially in reclaimed land has become one of the essential means of improving agricultural economic policy in many countries including Egypt, and The European Conference on Crop Diversification in 2019 reflects the importance of the concept. Hence, it is worth to question about the growth preference of weeds in response to this environmental factor. Furthermore, no one denies the importance of crop seasonality as one of the main drivers affecting weed community structure, and soil type and properties are undoubtedly among the major environmental factors influencing the structure of plant communities including weeds in a given area (Dale et al., 1992; Hoveizeh, 1997; Mahgoub, 2019b). In the current study both multivariate analysis and ordination techniques were employed. Several ecologists support the significance of the above mentioned methods in describing the relationship between a set of samples based on their attributes (Streibig, 1979; Salonen, 1993; Andersson, and Milberg, 1998; Anderson, 2001, 2006; and Clarke and Warwick, 2001).

2. Materials and methods

2.1. The study area

2.1.1. Geography

A sampling area was selected comprising the farmlands of Nile Delta (Egypt) as well as the east and west territories adjacent to them. Nile Delta can be considered as the region maintaining the major percentage of agricultural lands of Egypt since governmental reports have indicated that ≈ 61% of priority reclaimable land (through the Nile waters) is located on the fringes of the Delta, where in many localities the existence of loamy soil enhances plant growth and allow achievement of relatively successful cultivations (Biswas, 1993). The sample area is teardrop shaped (C. ≈ 27,231 Km^2 (10,514 mi^2), Fig. 1). The base of the Nile Delta represents the northern side and it covers some 240 km of Mediterranean coastline: from Alexandria in the west (coordinates: 31°12′27.3″N, 29°55′09.0″E; Latitude: 31.207592, Longitude: 29.919168) to Port Said in the east (31°16′09.6″N, 32°18′04.1″E; Lat, Long: 31.269344, 32.301133). The Suez Canal borders the study area from the eastern side, while western side of the area is bordered by the Western Desert. The length of the delta from north to south is approximately 160 km: from Baltim in the north (31°33′19.7″ N, 31°05′45.3″ E; Lat, Long: 31.555461, 31.095909) southwards to Cairo (30°02′40.9″ N, 31°14′07.3″ E; Lat, Long: 30.044698, 31.235365). Sample area includes several types of cultivated lands: fertile lands of the Nile Delta, farmland facing the Nile, farmland at the fringes of salt marshes, those facing Mediterranean Sea nearby the littoral sand dunes, reclaimed land in west-delta region near to the western desert, and those reclaimed land facing Suez Canal and Sinai Peninsula.

2.1.2. Climate

The Meteorological records of the area (2000 to 2018) were obtained as a courtesy, from the Egyptian Meteorological Authority "EMA". The Nile Delta has relatively moderate temperatures with highest usually not surpassing of 31 °C in the summer, and with cooler temperatures and some rain it becomes relatively-quite humid during the winter months. In general, the study area experiences its hottest temperatures in July and August, with a maximum average of 34 °C. Winter temperatures are normally in the range of 9 °C at night to 19 °C in the daytime, and minimum temperature records usually don't seem to reach freezing. From 100 to 200 mm of rain falls on the delta area during an average year, and most of these falls in the winter months. The northern part is the wettest. From the beginning of winter season (end of October) and until the beginning of May, the northwestern delta area is exposed to 21-squalls. They are usually accompanied with lightning thunderstorms, low temperature, high wind speeds, and cloud bursts, which produce heavy rain showers. However, Egypt essentially has a hot desert climate (BWh; Köppen, 1936 / Peel et al., 2007), and the records of the southern meteorological stations lying away from the water bodies of the Mediterranean Sea give an express of drier atmosphere, and higher rates of evaporation.

2.1.3. Soil type

The sixty-four sampling sites were classified according to the **Unified Soil Classification System** (USCS; Casagrande, 1948; ASTM, 1985, 2006) into two major site typologies based on a particle-size analysis and proportions of soil separates: sand, silt, and clay. This classification is one of the most common engineering soil classification systems used in engineering and geology to describe the texture and grain size of a soil in North America. The first site typology includes sampling sites which are characterized by **fine grained soil** (FGS) i.e., soil which contain more than 50 percent fines (silt and clay), while the second one includes sampling sites which are characterized by **coarse grained soil** (CGS) i.e., soil which contain 50 percent or less fines (including gravel soil and sandy soil). The chemical and mechanical soil analyses of the sites and localities of the study area are quoted according to those reported by the Ministry of Agriculture and Land Reclamation (MALR), Department of soil survey, Egypt, for the respect of its authority and farmers property. The depth of soil horizon profiles was: 0–30, 30–60, 60–90, 90–120 cm. The four samples which are collected from each locality of the site are pooled together to form a single composite sample, spread over sheets of paper, and left to dry in the air. The dry soil is passed through a 2 mm sieve then packed into paper bags for physical and chemical analyses. The following soil physico-chemical properties were included: 1) soil texture expressed as percentage for clay, silt, clay + silt, fine sand, coarse sand and it is measured according to the method of Allen et al. (1974), 2) water holding capacity (WHC; 100 gm soil %) and it is estimated according to Piper (1950), 3) hydrolytic conductivity (HC; cm./hour) and gauged by using a conductivity meter (Piper, 1950), 4) soil reaction (pH) and it is measured using pH meter (Pramer and Schmidt, 1984), 5) main salts in water saturated soil extract: for cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and they are determined according to the methods described in Jackson (1962), Black et al. (1965), and for anions ($CO3^{-2}$, $HCO3^{-}$, Cl^{-}) they are determined following those described in Allen et al., 1974; Maff, 1986; Hazen, 1989) 6) total soluble salts percentage (TSS) and it is estimated according to the method described in Black et al., (1965) and (7) calcium carbonate content (CaCO3) which is estimated according to the method described in Horváth et al. (2005) The results of the analyzes revealed that does not prevail one soil type in all sampling sites and that there were sites consisted of a mixture of different soil types. Accordingly, the "weight average" was calculated to express the physical and chemical soil properties which dominate a certain area.

2.2. Field sampling design, data collection and data proceeding

Sixty-four georeferenced sampling sites (districts) were randomly selected according to a stratified sampling technique (Müller-Dombois & Ellenberg, 1974: pp. 177-209), in order to represent 12 governorates of Nile Delta and the territories adjoining their east and west sides (refer to Fig. 1). Three villages were selected in each sampling site to represent the different types of cultivated lands. In each village, field plots (*relevés*; Poore, 1955; *The relevé method*, Minnesota Department of Natural Resources, 2013) with a size of 1000–1500 m^2 were studied in the cultivated crops. Thirty agroecosystems were defined at the level of cultivated crops: nineteen agronomic crops and eleven horticultural crops (orchards). Field data were collected in sequential seasonal excursions during 2018: three visits were realized during the winter half of the year (from December to May: in January, March, and April), and three visits during the summer of the same year (from June to November: in June, August, and September).

The agronomic crops were categorized based on their seasonality into three categories: eight winter crops (WC; sown in Autumn and harvested in early Summer), nine summer crops (SC; sown in Spring and harvested in Autumn), and two perennial crops (PC; occupy the field for one or more than one year). The horticultural crops were categorized at genus level into eleven orchard crops (OC). During analyses, each crop was denoted via a code consisting of the first two letters of crop-name in English. Likewise, each of the recorded species is denoted via a code consisting of a combination of the first two letters of genus name with the first two letters

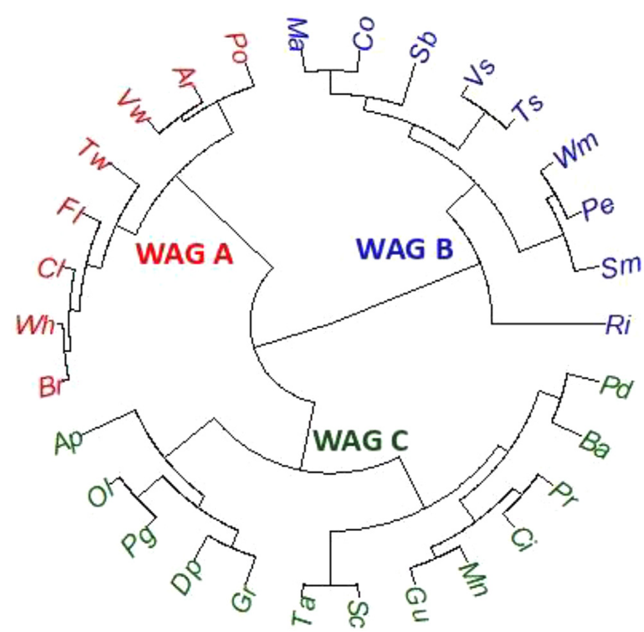

Fig. 2. Fan-shaped dendrogram representing cluster analysis (AHC) for weed assemblages associated with the 30 crops (agroecosystems) surveyed (for crop legend, refer to synoptic table Appendix 1).

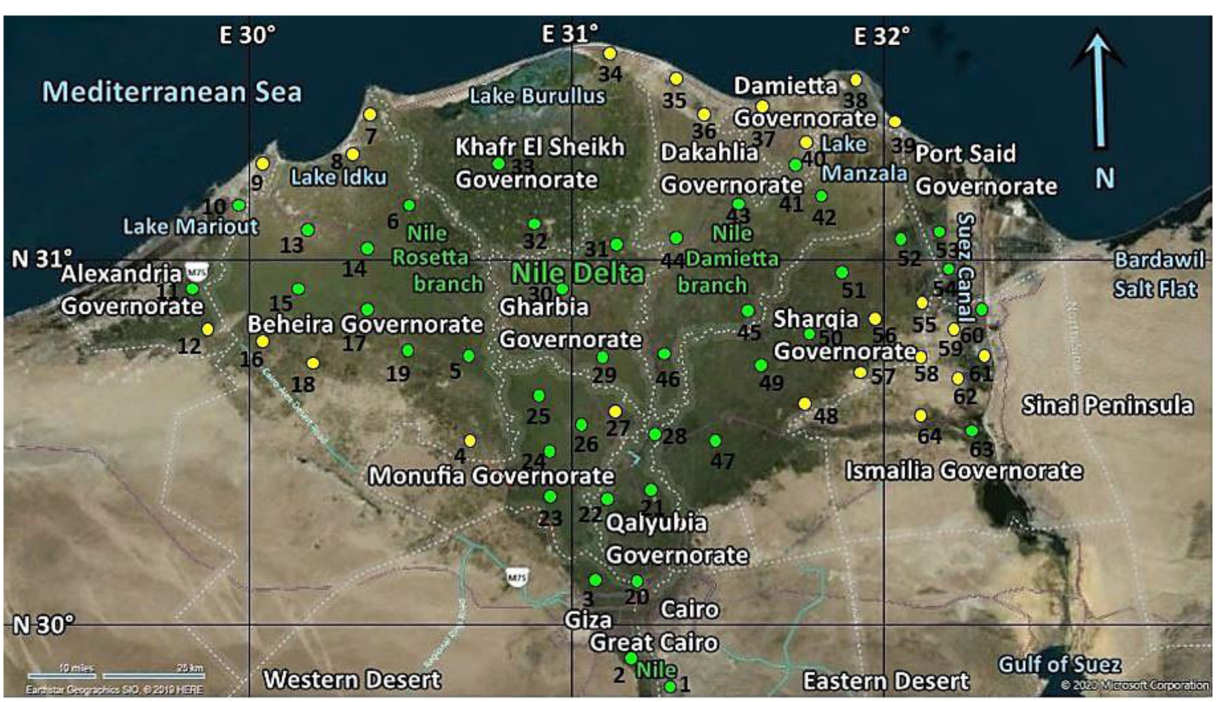

Fig. 1. Location Map of the surveyed area. Sixty-four georeferenced sampling sites (districts) were selected in 12 governorates in order to represent 30 agronomic and horticultural crops cultivated under different environmental conditions. Sampling sites which are characterized by fine grain soil (FGS) are represented by green dots (40), while those characterized by coarse grain soil (CGS) are represented by yellow dots (24). For legend of sampling sites and governorates, refer to synoptic table, Appendix 1). "Map adapted from Bing Maps. Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation. © 2021 Microsoft".

of species name, while in case of similarity between abbreviations the letters used for coding of the respective species were the next in the series of letters of the name (for botanical nomenclature and legend of codes, refer to synoptic table - Appendix 1). Some crops have two types of cultivations e.g., Tomato which is cultivated as a winter crop in sandy soils and as a summer crop in clay and clay loamy soils, and several genera of the monitored orchards included more than one cultivated species, subgenera, or varieties (refer to Appendix 1, e.g., *Citrus* (*C. sinensis*, *C. reticulata L. var.*) and *Prunus subg. Amygdalus*).

The frequency and abundance values of the recorded species (**555 *sp.***) were calculated according to Curtis, and McIntosh (1950). The sample data from all the investigated *relevés* that concern frequency, and abundance, of each species were added together and the average was considered to constitute an adequate sample of a selected species in a community. **150 species were evaluated as the most influential weeds in the structure of weed communities** associated with agronomic and horticultural crops based on the criteria of their importance values, scoring either relative frequency (Fr) $\geq$ 30% or mapped to abundant or very abundant classes (Ab $\geq$ 30), in at least one of the **four crop categories** (WC, SC, PC, OC; refer to synoptic table - Appendix 1). The Fr/Ab values of species and their **coefficient of variation** (C_v; Hendricks, and Robey, 1936, see also Krishnamoorthy, and Meesook, 2013) were calculated for the pool of all groups. Furthermore, the index of winter and summer recurrence (WRI%, SRI%, respectively) was gauged and accordingly their **species seasonality** (SS) was determined. They were designated as all-the-year-round weeds (A), or winter weeds (W, or Ws), or summer weeds (S, or Sw) and **seasonal bias percentage** (Sb% / +, -) was calculated following the approach of Mahgoub (2019a, 2019b).

The above-mentioned parameters were used to the **Multivariate analyses (MVA)** and the **ordination techniques** in order the preference of weed growth in response to crop seasonality and diversification (**CRDIV**) to be evaluated. The importance values (Fr/Ab) in the four crop categories in addition to species seasonality and seasonal bias percentage were used to assess the preference of weed growth in response to **crop seasonality**, while Fr/Ab values for pool all groups and coefficient of variation were used as an expression for the preference of weed growth in response to **crop diversification**.

Indicator species analysis (ISA) was employed for the determination of weed species preference in the different soil types found in study area. Although several methods of identifying indicator species have been proposed (e.g., Hill, 1979; Carleton et al., 1996), the ISA method of Dufrêne, and Legendre seems to be the most appropriate in our case because its use allows identification of indicator species and species assemblages characterizing groups of sites (Dufrêne, and Legendre, 1997). Contrary to TWINSPAN (Hill, 1979) in which species are classified based on their concentrated occurrence to a certain typology of sites (fidelity of species to groups of sites), except of indicator species identification, enables also the calculation of **fidelity and specificity** of weeds to a priori identified typology of sites (e.g., FGS/CGS). According to this approach, species recorded were evaluated considering the two site typologies identified according to USCS, viz., **fine-grained soil** (FGS) and **coarse-grained soil** (CGS), then **indicator value of each species** (*INDVAL*) was calculated and an **indicator value index** was constructed. An arbitrarily threshold level of *INDVAL* $\geq$ 25% was chosen for the identification of **strong indicator species** of the groups in accordance to the followed approach with the aim of excluding and discarding very weak species. However, the evaluation of a species as a strong indicator in relation to another one, also encompasses the extent of its ecological success. Thus, an additional filter was applied in the current study and **strong indicator species** were specified as those which in one of two typologies had got *INDVAL* with a value $\geq$ 25% and at least twice as high than in the other. Such manipulation coincides with the acceptance of Bergmeier et al. (1990) who define as diagnostic the species whose frequency in a particular vegetation unit is at least which is the difference between a species frequency and a frequency class than in the other vegetation units. The codes of these species viz., strong indicator species are framed with a gray background, and the effectiveness of them was measured on basis of their absolute values in the **preference index** (*PRFIND*; Hill, 1979) where the highest is the strongest i.e., the **best of the strong indicator species** (refer to synoptic table - Appendix 1, Fig. 3).

The Nomenclature of recorded taxa follows Täckholm (1974) as well as Boulos (2009) to a more recent Plant List, created by the Collaboration between the Royal Botanic Gardens (Kew), Missouri Botanical Garden (MO) and other collaborated institutions, Version 1.1, September 2013. The collected specimens were identified in *Cairo University Herbarium (CAI)*, where they deposited as Herbarium specimens and numbered by serial collecting number (*MAHGOUB'S collecting number*).

2.3. Diversity and Biostatistics

The following software were used during **Multivariate analyses (MVA)**, and ordination techniques: VEGAN packages (Oksanen et al., 2016; in R environment, ver. 3.6, 2019), JUICE (Tichý, 2001; ver. 7.1, 2020), PAST (Hammer et al., 2001; ver. 4, 2020), CANOCO (ter Braak & Smilauer, 2002; ver. 4.5, 2007).

Agglomerative Hierarchical Clustering (AHC) was employed as a clustering technique. The data were standardized prior to analyses and Euclidean distance was used as a measure of dissimilarity while Ward's method (Minimum-variance clustering) as an agglomeration criterion (Orlóci, 1978). The program firstly constructed a classification of the 30 agroecosystems (crops) based on variation of floristic composition of weed assemblages associated with them, then used this classification to assign the 555 weed species into vegetation units or weed communities, or **Weed Assemblage Groups (WAG).** The identified vegetation units (weed assemblage groups/WAG) were named after the two most predominant species (Whittaker, 1962). Fidelity between the 150 most influential weed species and the identified vegetation units (WAG) was measured by the **phi-coefficient of association** (Φ; Sokal & Rohlf, 1995; Chytrý et al., 2002). Quantitative fidelity measures were applied in the Indicator Value formula (*INDVAL*), and chi-square statistic was used for checking the statistical significance of result (Pearson, 1900, see also Sokal & Rohlf, 1995: 697, 736; Ryabko et al., 2004), at a level of significance of 0.05 (X^2: α = 0.05, P^* > 3.841; refer to synoptic table - Appendix 1). Within the groups of vegetation units (WAG), number of associations were specified of less-common (differential) species recognized at the level of alliances. They characterize the weed community structure associated with some crops in one or more sites (districts) and the record of them is related to a specific ecological condition (ecological niche). In these **within-group associations** (alliances), the dominant species of the vegetation units (WAG) had lowest abundance values along with a remarkable increase in those of the species constituting these alliances. These within-group associations were specified by tabular comparison technique of species abundance and occurrence across sites/crops (Shaltout et al., 1992), and they were named according to Whittaker's approach (1962) either.

The **Diversity** for both the vegetation units (WAG) and alliances was evaluated at different levels. The following diversity indices were measured: Species richness (S) "*Taxa_S*" (Magurran and McCarthy, 2004, see also Chao, 2005), Shannon-Wiener diversity index (H) "Shannon_H" (Shannon & Weaver, 1949, see also Pielou, 1975), Equitability I "Equitability_J" (Hill, 1973, see also

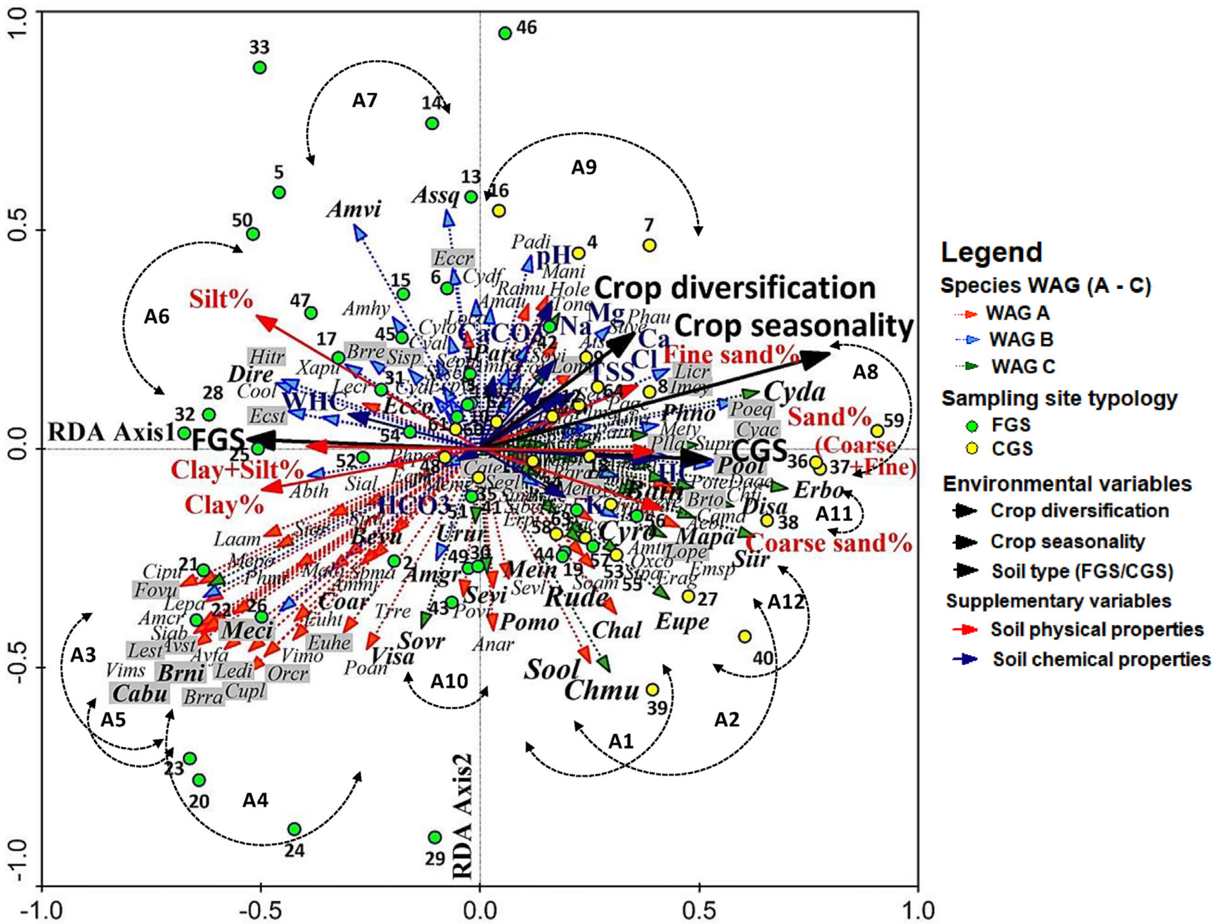

Fig. 3. Triplot RDA correlation displaying ordination of species/sites/environmental variables on RDA axis1 and on RDA axis2. Objects occur as points while variables as vectors. Species points are symbolized by triangles, while those of sites as circles. The species of weed assemblage groups (WAGA - WAGC), and typology of sites are superimposed. Each arc indicates a specific environmental condition (ecological niche) in which an alliance (A1 - A12) was recorded. The symbols of dominant species of the WAGs (A – C) and of the alliances (within-group associations) are given in bold, while those corresponding to the strong-indicator-species are framed by gray background (for codes, refer to Table 1 and Appendix 1).

Chao et al., 2005), and Dominance (D) "Dominance_D" (Simpson, 1949, see also Harper, 1999). **Beta diversity (β; Whittaker, 1960**, see also Lande, 1996, reviewed in Koleff et al., 2003) and **Jaccard similarity coefficient (Jaccard index (*J*)**; Jaccard, 1901, 1912, see also Real, 1999; Tan et al., 2005) to estimate compositional differentiation and similarity of WAG and the within-group associations, respectively. To demonstrate the effect of seasonality on the resulted vegetation units (WAG), the **absolute species turnover** (β_A; Whittaker, 1972, see also Lande 1996; Tuomisto, 2010; Albert & Reis, 2011) was gauged depending on the presence - absence data among the two seasonal subunits, viz. winter weed community / summer weed community, and the result was tested for statistical significance ($P < 0.05$).

In order to be chosen an appropriate ordination method for achieving a direct gradient analysis the rule of thumb introduced by Lepš & Šmilauer (2003) was applied. **Detrended correspondence analysis** (DCA; Hill & Gauch, 1980) estimated the compositional gradient in the vegetation data of the present study to be < 4 SD (standard deviation units), thus, **redundancy analysis** (RDA; Van den Wollenberg, 1977) is the appropriate ordination method to perform direct gradient analysis (ter Braak & Prentice, 1988). The algorithm was used to extract and summarize the variation in species records in the response matrix (species vs. sites) that can be explained by the three environmental variables (explanatory matrices; soil type FGS/CGS, crop seasonality, and crop diversification). However, for careful design of the experiment and more informative results, the soil physicochemical properties were employed as supplementary variables for soil type. These variables include: Clay%, Silt%, Clay + Silt%, Coarse sand%, Fine sand%, Coarse + Fine sand%, WHC, HC, pH, TSS, Ca, Mg, Na, K, Cl, HCO3, CaCO3. A **Monte Carlo permutation test** (499 permutations under reduced model; ter Braak, 1990) was used to test for the statistical significance of the model and the eigenvalue of the first axis (RDA axis 1). The result of the analysis was represented by RDA correlation triplot for species, sites, and environmental variables (Fig. 3). **Variation partitioning** (VP; Borcard et al., 1992, see also Zelený, 2019) was employed in combination with RDA, and the variation was partialized out to determine the partial, linear effect of the three ecological preferences. The explained variation was compared by adjusted R^2 values, and the significance of fractions of interest was tested by applying **ANOVA** (permutation test for RDA under reduced model, 999 permutations), and the result of the analysis was displayed as Venn diagram (Fig. 4).

3. Results

3.1. Weed growth in response to crop seasonality

A total of 555-species were enumerated in the present study. They belong to 282-genera distributed among 58-families. More

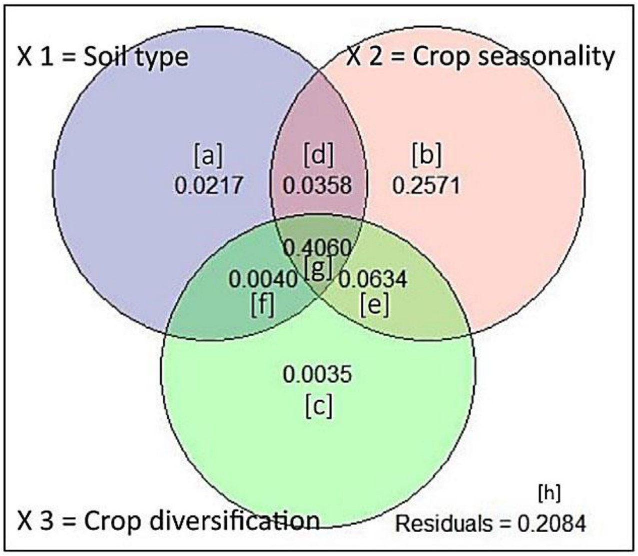

Fig. 4. Venn's diagram, showing partition of the variation explained by the preference of species to the three environmental variables (79.16%). Adjusted R^2 was used for comparison of the marginal and conditional effect of the explanatory variables and the individual fractions.

than half of these species were recorded during winter (≈ 65% or 358-species) and most of them from annuals (≈ 85%). During summer 118-species (≈ 21%) were recorded, and the remaining 79-species (≈ 14%) were recorded as weeds present in crops all-the-year-round. Agglomerative Hierarchical Clustering (AHC) aggregated the weed assemblages associated with the 30 agroecosystems (crops) in three groups or WAG (Fig. 2) based on their floristic composition. The first group WAG A or group *Sonchus oleraceus – Rumex dentatus* included the weed assemblages associated with agronomic winter crops, and the second group WAG B or group *Bassia indica – Cyperus rotundus* included those associated with agronomic summer crops, while the third group WAG C or group *Cynodon dactylon – Chenopodium murale* included weed assemblages associated with agronomic perennial crops and horticultural crops (orchards). The measurement of diversity indices of these weed assemblage groups revealed that WAG C scored the highest species richness (S = 292), highest Shannon Wiener diversity index (H = 5.60), highest Equitability (E = 0.92), and the lowest Dominance (D = 0.005). On the other hand, WAG B scored the lowest S (=103), lowest H (=5.09) and the highest D (=0.009), while WAG A scored intermediate estimates (refer to Table 1). Whittaker's Beta (β) diversity index pairwise comparisons showed that WAG C had gained a higher heterogeneity in species composition as compared pairwise with WAG B than when compared with WAG A, while WAG A and WAG B were less dissimilar in species composition at the pairwise comparison (Global β diversity, Whittaker: 0.521; refer to Table 2). The absolute species turnover among the two seasons of year (winter/summer) was scored as follows: βA = 39.13 ± 3.43, DivInd = 65.7 ± 1.184, and it was statistically significant at a level of significance of 0.05.

The measurement of the statistical fidelity of species using phi-coefficient (Φ) indicated that out of the 150 weeds which were specified as influential, 61-species were faithful to WAG A, 45 to WAG B and 44 to WAG C, while 33 of these species had statistically significant joint fidelity to their groups (WAG A – C) at a level of significance of 0.05 (X^2**:** $\alpha = 0.05$, $P^* > 3.841$). The other measured ecological parameters of weeds indicate the significant effect of crop seasonality on the preference of weed growth either. The measurement of species seasonality (SS) of the most influential weeds (index of winter and summer recurrence, WRI%/SRI%; Mahgoub, 2019a, 2019b) indicate that 87-species assigned as winter weeds of them 64-species are annuals (W) while 23-species showed tangible growth in the corresponding other half of the year (Ws), while 44-species assigned as summer weeds of them 27-species are annuals (S) and 17-species showed tangible growth in the corresponding other half of the year (Sw), and 19 species as all-the-year-round weeds (A). The measurement of the seasonal bias (Sb%) of these species also reveal that 27- species showed a seasonal bias of at least 25%. of them 16 are winter weeds, 10 are summer weeds and one of the all-the-year-round weeds (refer to synoptic table – Appendix 1). This category of weeds includes five of the six most predominant species of WAG (A - C), which are: the two predominant species of the WAG A (*Sonchus oleraceus*: Sb% = + 47.2, *Rumex dentatus:* Sb% = + 41.1), those of WAG B (*Bassia indica*: Sb% = − 42.5, *Cyperus rotundus*: Sb % = −26.1), and *Chenopodium murale* (Sb% = + 48.1) which is one of the two predominant species of the WAG C. As for the second predominant species of WAG C (*Cynodon dactylon*) it scores Sb% = −6.8. However, the highest seasonal bias (Sb%) during the winter was scored by *Sinapis alba* (Ws; Sb% = + 68.3) and *Senecio glaucus* (W; Sb% = + 83.2) in Winter-tomato cultivation and Date palm orchards, respectively, while the highest Sb% during the summer was scored by *Echinochloa colona* (Sw; Sb% = − 48.7) and *Erigeron bonariensis* | *Digitaria sanguinalis* (Sw, S; Sb% = − 28.3%) in Maize fields and Mango orchards, respectively.

3.2. Weed growth in response to crop diversification

The likely association of a certain species with certain crop(s) becomes also eminent through the records of species (Fr /Ab), which show that although such a correlation was a reality for one or more cultivations, in some others it was weak or absent. Thirty-four of the most influential weeds showed such significant ecological preference for growth in response to crop diversification (CRDIV) as they scored coefficient of variation of at least 100% i.e., $Cv \geq 100\%$ (refer to Appendix 1). They showed ecological preference for growth in fields cultivated with 13 agronomic and horticultural crops, as follow: *Phalaris paradoxa* was common in Wheat; *Brassica nigra*, *Cichorium pumilum* were common in Clover; *Phalaris paradoxa*, *Orobanche crenata* were common in Broad bean; *Lepidium sativum*, *Sinapis arvensis*, *S. allionii*, *Matthiola longipetala* were common in Flax; *Silene behen* was common in Winter-tomato; *Abutilon theophrasti*, *Sesbania sesban*, *Corchorus olitorius* were common in Cotton; *Amaranthus cruentus* was common in Maize; *Eclipta prostrata*, *Echinochloa crus-galli*, *E. stagnina*, *E. pyramidalis*, *Cyperus difformis*, *C. alopecuroides*, *C. dives*, *Ammannia baccifera*, *A. auriculata* were common in Rice; *Brachiaria deflexa* was common in Peanut; *Ambrosia maritima* was common in Watermelon; *Brachiaria reptans*, *Sorghum virgatum*, *Foeniculum vulgare*, *Leptochloa panicea*, *Oxalis corniculata* were common in Banana; *Setaria pumila*, *Oxalis corniculata* were common in Mango; *Mesembryanthemum nodiflorum*, *M. crystallinum*, *Cakile maritima*, *Rumex pictus* were common in Date palm.

3.3. Weed growth in response to soil type

Forty of the sixty-four sampling sites studied in total were classified as FGS. The remaining twenty-four sites were assigned into CGS typology (Fig. 1). ISA highlights that the ecological preference for growth of the most influential weeds was affected by soil type to varying degrees, as well. Sixty-six species showed ecological preference for growth in fine grained soil (i.e., *INDVAL* FGS > *INDVAL* CGS), while eighty-four species showed ecological preference for growth in coarse grained soil (i.e., *INDVAL* CGS > *INDVAL* FGS). Of these, 94-species surpassed the ISA arbitrarily threshold level for the identification of strong indicator species

Table 1
Syntaxonomic table illustrating the spatial distribution and classification of the 12 alliances (A1 - A12) which are recorded in WAG (A - C).A total of 555 species enumerated in WAG from which 150 species were evaluated as the most influential weeds (INFSP). Within the vegetation units (WAG), twelve alliances (within-group associations) are specified and the record of them match to a specific environmental condition (ecological niche). In these alliances twenty-nine species are identified as strong indicators (SINSP) and they are listed in order according to their effectiveness based on their values in the preference index (*PRFIND*). The diversity indices and ecological criteria for both the alliances and WAG are also included in the table and the maximum values are in bold text: S = Species richness, H = Shannon-wiener diversity index, E = Equitability, D = dominance, W = Winter weeds, A = All-the-year-round weeds, S = Summer weeds, Ws/Sw = winter and summer weeds which showed tangible growth in the corresponding other half of the year, FGS = Fine grain soil, CGS = Coarse grain soil, ≈ = convergent values (for values of *PRFIND*, legend of crop code and location of sites (districts), refer to synoptic tabl Appendix 1 & location map – Fig,. 1).

	Classification scheme of Alliances (A1 - A12) / Weed assemblage groups (WAG A - WAG C)	Species codes	Preferred site typology (FGS/ CGS)	Ecological niche (special environmental condition)	Ecological niche (special environmental condition)	Preferred Crop type / Crop Category	Species Seasonality					Diversity Indices				No. of INFSP	Strong indicator species (SINSP)	
							W	**Ws**	**A**	**S**	**Sw**	S	**H**	E	D		Number of species	
WAG A	***Sonchus oleraceus – Rumex dentatus***	***Sool–Rude***				***WC***	**121**	**21**	**12**	**4**	**2**	**160**	**5.29**	0.89	0.007	**61**	**16**	
A1	*Polypogon monspeliensis – Chenopodium album*	*Pomo–Chal*	CGS	high HCO3, low K^+, fine sand %	18, 35, 37, 39, 58, 59, 62	*Cl, Tw*	87	20	9	3	**2**	121	4.25	0.89	**0.018**	57	1	*Raphanus raphanistrum*
A2	*Melilotus indicus – Malva parviflora*	*Mein–Mapa*	CGS	high HCO3, K^+, HC, fine + coarse sand %	7, 9, 34, 38, 40, 48, 58, 59	*Cl, Br, Tw*	82	17	9	1	1	110	4.28	**0.91**	0.017	51	4	*Brassica tournefortii, Lolium perenne, L. multiflorum, Plantago lagopus*
A3	*Convolvulus arvensis – Beta vulgaris*	*Coar–Bevu*	FGS	high HCO3, WHC, clay + silt %, low sand %	3, 13, 14, 29 - 32, 41, 43, 46, 50, 60	*Wh, Br, Ar*	101	19	10	1	**2**	133	4.35	0.89	0.016	57	3	*Euphorbia helioscopia, Foeniculum vulgare, Avena sterilis*
A4	*Vicia sativa – Brassica nigra*	*Visa–Brni*	FGS	high HCO3, clay ≈ silt ≈ sand %	29, 30	*Cl, Po*	**104**	20	**11**	**4**	**2**	**141**	**4.47**	0.90	0.015	58	3	*Brassica rapa, B. nigra, Orobanche crenata*
A5	*Medicago intertexta subsp. ciliaris – Capsella bursa-pastoris*	*Meci–Cabu*	FGS	high HCO3, high clay and low silt, sand %	29 -31	*Cl, Fl, Po*	94	**21**	9	3	**2**	129	4.36	0.90	0.016	**59**	**5**	*Medicago intertexta subsp. ciliaris, Capsella bursa-pastoris, Cuscuta planiflora, Lepidium didymum, L. sativum*
WAG B	***Bassia indica – Cyperus rotundus***	***Bain–Cyro***				***SC***	**6**	**2**	**16**	**58**	**21**	**103**	**5.09**	0.90	0.009	**45**	**9**	
A6	*Echinochloa colona – Dinebra retroflexa*	*Ecco–Dire*	FGS	high clay + silt %, WHC, pH , low sand %	21, 23, 24, 25, 26, 28, 32, 33, 49, 50	*Co, Ma, Ri*	3	0	15	33	**21**	72	3.74	0.88	**0.030**	**43**	**4**	*Hibiscus trionum, Sida spinosa, Echinochloa stagnina, Brachiaria reptans*
A7	*Aster squamatus – Amaranthus viridis*	*Assq–Amvi*	FGS	high CaCO3, pH, clay ≈ silt ≈ sand %	2, 5, 10, 11, 13, 17, 32, 33, 49	*Co, Ma, Ri*	4	0	14	28	17	63	3.74	0.90	0.029	40	1	*Echinochloa crus-galli*
A8	*Phyla nodiflora – Portulaca oleracea*	*Phno–Pool*	CGS	high TSS, Ca^{++}, Mg^{++}, Cl^-, HC, fine + coarse sand %	34, 35, 38	*Ma, Ts, Vs, Sm*	**6**	1	**16**	51	19	93	**4.13**	**0.91**	0.020	42	2	*Polygonum equisetiforme, Portulaca oleracea*
A9	*Panicum repens – Amaranthus graecizans*	*Pare–Amgr*	CGS	high Na^+, Mg^{++}, pH, fine sand %	56, 59	*Ma, Pe, Wm, Sm, Vs*	**6**	1	**16**	**54**	19	**96**	**4.13**	**0.91**	0.020	**43**	2	*Imperata cylindrica, Limbarda crithmoides*
WAG C	***Cynodon dactylon – Chenopodium murale***	***Cyda–Chmu***				***PC + OC***	**176**	**29**	**51**	**29**	**7**	**292**	**5.60**	**0.92**	0.005	**44**	**4**	
A10	*Sorghum virgatum – Urtica urens*	*Sovr–Urur*	FGS	high HCO3, K^+, clay ≈ silt ≈ sand %	41, 44, 47	*Ba, Gu, Mn, Pd*	70	**18**	32	18	**6**	144	4.50	0.91	0.016	38	1	*Cynanchum acutum*
A11	*Erigeron bonariensis – Digitaria sanguinalis*	*Erbo–Disa*	CGS	high TSS, Ca^{++}, Mg^{++}, Cl^-, HC,	16, 35 - 38, 48, 58, 61, 62	*Gu, Mn, Dp, Gr*	26	8	11	10	5	60	3.75	**0.92**	**0.031**	31	1	*Mesembryanthemum nodiflorum*

(continued on next page)

Table 1 (*continued*)

	Classification scheme of Alliances (A1 - A12) / Weed assemblage groups (WAG A - WAG C)	Species codes	Preferred site typology (FGS/ CGS)	Ecological niche (special environmental condition)	Ecological niche (special environmental condition)	Preferred Crop type / Crop Category	Species Seasonality					Diversity Indices				No. of INFSP	Strong indicator species (SINSP)	
							W	**Ws**	**A**	**S**	**Sw**	S	**H**	E	D		Number of species	
				fine + coarse sand %														
A12	*Euphorbia peplus – Sisymbrium irio*	*Eupe–Siir*	CGS	high K^+, Ca^{++}, Cl^-, TSS, HC, fine + coarse sand %	35 - 40, 48	*Ci, Gu, Pr, Mn, Ap*	**90**	**18**	**36**	**20**	**6**	**170**	**4.67**	0.91	0.014	**40**	**2**	*Senecio glaucus, Carthamus tenuis*

Table 2
Whittaker's Beta (β) diversity index pairwise comparisons for WAG (A - C). Global beta diversity, Whittaker: 0.521.

	WAG A	WAG B	WAG C
WAG A	0		
WAG B	0.287	0	
WAG C	0.300	0.357	0

proposed by Dufrêne and Legendre (*INDVAL* ≥ 25%), and of them 29-species were accepted in the present study. These twenty-nine species included 16-species assigned as strong indicators for fine grained soil (*INDVAL* ≥ 25%, FGS ≥ 2 CGS), and 13-species for coarse grained soil (*INDVAL* ≥ 25%, CGS ≥ 2 FGS), refer to synoptic table - Appendix1.

3.4. Weed growth in response to the combined effect of the three decisive environmental variables

The Fr /Ab importance values of species measured in the raw data set, and those presented in the synoptic table (Appendix 1) reveal that the records of the six most predominant species in WAG categories (A - C) differ between sites with different typology as well as from the one crop-category to the other. Although they were recorded in all crops during the favorable growth season of them (Fr = 100%), however they had lowest abundance values when some crops have been cultivated in one of the two site typologies where a specific environmental condition prevails (e.g., high soil content in CaCO3, $HCO3^-$, Na^+, K^+, coarse sand, silt, high pH, ……. etc.).

This disparity in the performance of the six predominant weeds was recorded along with the prevalence of twelve alliances or within-group associations (A1 - A12) of less-common (differential) species (refer to Table 1, Table 3 & Fig. 3). The recording of each of these alliances matches to the presence of a specific ecological condition (ecological niche). Five of them (WAG A/ A1 – A5) were recorded in agronomic winter crops grown in soil with high HCO3 content. The first two weed communities A1 (association *Polypogon monspeliensis – Chenopodium album*) and A2 (association *Melilotus indicus – Malva parviflora*) were recorded in Tomato, Clover and Broad bean which were cultivated in CGS, however the occurrence of the A2 community matched to more specific ecological condition of higher soil content in K and coarse sand. The three other weed communities (A3 or association *Convolvulus arvensis – Beta vulgaris*, A4 or association *Vicia sativa – Brassica nigra* and A5 or association *Capsella bursa-pastoris – Medicago intertexta* subsp. *ciliaris*) were recorded in Clover, Wheat, Artichoke and Potato cultivated in FGS. However, the record of A3 community is related to a higher soil content of clay and silt than A5 and A4 communities, respectively. The A4 community presented the highest species richness (141 *sp.*), while A5 included the highest number of influential weeds (59 *sp.*). The measurement of the degree of similarity in floristic composition between these weed communities by Jaccard similarity coefficient (*J*) revealed that *J* (A1, A2) was not statistically significant at $P < 0.05$, while J (A3, A4) & J (A3, A5) & J (A4, A5) were statistically significant and the highest overlap was scored between communities A4 and A5 (*J* (A4, A5) = 81%). Surprisingly, community A1 which was recorded in CGS sites gained statistically significant *J* values with communities A3, A4 & A5 that were recorded in FGS sites (refer to Table 3). Four associations (WAG B/ A6 – A9) interrelated with agronomic summer crops. The first two weed communities (A6, A7) were recorded in Cotton, Maize and Rice cultivated in FGS sites. However, the community A6 (association *Echinochloa colona – Dinebra retroflexa*) was related with those farmlands that have high soil content of clay & silt, high

Table 3
Jaccard similarity coefficient (*J*) for the tweleve alliances (within-group assoications). Statistically significant *J*-values are in bold (P* < 0.05).

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
A1	1											
A2	0.55	1										
A3	**0.73***	0.59	1									
A4	**0.84***	0.69	**0.71***	1								
A5	**0.92***	0.53	**0.71***	**0.81***	1							
A6	0.44	0.37	0.43	0.41	0.44	1						
A7	0.55	0.49	0.54	0.53	0.53	0.53	1					
A8	0.49	0.43	0.48	0.49	0.47	0.45	0.54	1				
A9	0.56	0.47	0.56	0.54	0.55	0.53	0.63	**0.71***	1			
A10	0.54	0.55	0.52	0.54	0.51	0.43	0.66	0.50	0.50	1		
A11	0.39	0.43	0.38	0.34	0.35	0.43	0.47	0.36	0.40	0.51	1	
A12	0.56	0.52	0.53	0.57	0.54	0.43	**0.80***	0.56	0.57	**0.86***	0.45	1

WHC values and high pH (alkaline soils), while A7 (association *Aster squamatus – Amaranthus viridis*) was more frequent in soils characterized by high content of CaCO3 and high pH (calcareous soil). The other two weed communities A8 (association *Portulaca oleracea – Phyla nodiflora*) and A9 (association *Panicum repens – Amaranthus graecizans*) were recorded in Maize, Peanut, Watermelon, Sweet-melon, Summer- tomato, and Vegetables cultivated in CGS sites characterized by high soil salinity, however the latter community (A9) prevails in soils with high pH and high Na^{+} content (sodic soils). Community A9 scored the highest S (96 *sp.*) and included the highest number of INFSP (43 *sp.*) either. *J* (A6, A7) was not statistically significant, while the communities A8 and A9 shared high number of species and scored a statistically significant Jaccard similarity index value (*J* (A8, A9) = 71%). The remaining associations (A10, A11, A12) refer to WAG C. The first of these weed communities (A10 or association *Sorghum virgatum – Urtica urens*) was recorded during the winter season in Banana, Apricots, Nectarine, and peach orchards planted in FGS sites characterized by soils with high content of HCO3 and K. The two other communities A11 (association *Erigeron bonariensis – Digitaria sanguinalis*) and A12 (association *Euphorbia peplus – Sisymbrium irio*) were recorded during the summer and the winter seasons of the year, respectively, in Guava, Mango, Date palm, Grape, Pear and Apple orchards grown in CGS sites characterized by high soil salinity. However, community A12 excelled in soils with high K content and had the highest S (170 sp.) and highest INFSP (40 sp.) either. *J* (A10, A12) was statistically significant and the probability of a species to be recorded in both communities was 86% (refer to Table 3). In these alliances, twenty-nine species were specified as strong indicators and they are ranked according to their effectiveness depending on their values in the preference index (*PRFIND*), refer to Table 1, synoptic table - Appendix 1.

RDA was successful in extracting and summarizing the variation of species importance values (Fr/Ab) in relation to the matrix of the identified Weed Assemblage Groups (WAG A -C), refer to synoptic table - Appendix 1. This variation can be attributed to species preference to the three environmental variables concerning soil type, crop seasonality and crop diversification. It should be reminded that the soil type, soil properties, crop seasonality and crop diversification are all environmental variables (not ecological preferences) that affect the weed growth. Thus, according to their preferences towards these variables the weeds are grouped into communities and then into community groups. Therefore, a species or community shows ecological preference or not in one of the above variables. The constrained variance was much higher than the unconstrained one, and the algorithm explained 79.16% of the total variance. The permutation test indicated that both the model and eigenvalue of RAD axis1, were statistically significant at $\alpha = 0.01$. The first axis explains 50.6% of the variation, while first axis along with the second one interpret the 69.3%. The RDA results which are displayed in the correlation triplot (Fig. 3) indicate that RDA axis1 can be interpreted as a sand–clay gradient, since it correlates positively with soil sand content (fine sand and coarse sand) and negatively with the clay content of the soil. As for RDA axis2, it is positively correlated with CaCO3 soil content, and negatively correlated with soil content in HCO3 & K. Thus, it can be interpreted as CaCO3–K/HCO3 gradient. The sets of objects scores and explanatory variables scores indicated that seasonality and diversification of crops had a stronger effect on the structure of weed communities associated with crops cultivated in CGS than that on the structure of those associated with crops on FGS. The length of the vectors of the explanatory variables shows that growth preference of most influential weeds seems to be more affected by crop seasonality rather than by crop diversification and soil type, and the angles between these vectors reflect the significance of their linear correlation. Conceiving the site objects ordination, we can realize that the littoral sites of Nile Delta were the most similar in species composition, followed by the remaining sites of Nile Delta region, and the sites of east and west adjoining territories. The distances between the points of species and sites for the six predominant species and their ordination in the triplot RDA correlation indicate that their relative abundance and probability of occurrence (predicted relative frequency) differed across sites. Four among these species (*Sonchus oleraceus*, *Chenopodium murale*, *Cyperus rotundus* and *Rumex dentatus*) show ecological preference for growth in sites of FGS typology, while two of them (*Cynodon dactylon* and *Bassia indica*) prefer sites of CGS typology for their growth. The two latter species also show a higher probability of occurrence in the sites with high soil salinity, low capacity of water holding (in the east and west territories of Nile Delta), than that the other four species which are more frequent in sites characterized by lower soil salinity, higher-water holding capacity and higher K soil content. The coordinates of their object points refer to their scores along the gradients of sand–clay (RDA axis1) and CaCO3–K/HCO3 (RDA axis2), and the projection of an ordinated point onto a variable vector, approximates the variable's value realised for that object. Visualizing the ordination of the object points in the RDA triplot for the two most predominant species in each of the twelve alliances recorded (A1 - A12) and those of the strong indicators also reveal the disparity in their performance in response to the three environmental variables and indicate the ecological conditions with which the presence of these alliances is related, as previously mentioned. The scores of their coordinates along RDA axis1/axis2 and the right-angled projections of their object-points onto vectors give an assessment of their preference for growth regarding soil type, crop seasonality and crop diversification.

Partitioning the variation between the three environmental variables (which are considered explanatory matrices reflecting the ecological preferences of investigated weed communities and interpret their distribution, see synoptic table - Appendix 1) in the matrix of species response indicated that the partial linear effect of crop seasonality on the response data greater than that of the other environmental variables. The adjusted R^2 values of the marginal and conditional effect of crop seasonality were 76.23% & 25.71%, respectively, while those of soil type and of crop diversification were 46.75% & 2.17%; 47.69% & 0.35%, respectively (refer to Fig. 4). The results indicated strong correlation between the three explanatory variables, and the shared variation explained by them was much higher (Adj.R^2 = 40.6%) than the shared variation explained by only two of them (Adj.R^2 = 0.4–6.34%). ANOVA results revealed that all simple (marginal) and conditional (partial) effects of the three predictors were significant at $P < 0.001$.

4. Discussion

Several phytosociological researches illustrated that the structure of weed communities is determined by the combined effects of a whole range of ecological factors (Mahgoub, 2019a; Gholinejad et al., 2012). Usually, it is structured mainly by edaphic qualities which characterize the soil itself (e.g., drainage, soil texture or chemical properties such as pH, soil salinity, ...etc.), climatic conditions, and crop seasonality which depends on crop genetic adaptation (Mahgoub, 2019b). However, the quest to bring new lands under cultivation is considered as the cornerstone for the agricultural policy in several countries. In Egypt, desert comprise about 95% of the total land surface and except for Nile Delta and the Fayium Oasis, only a narrow strip along the Nile is cultivated and the population is concentrated in these areas. It is not surprisingly that the land reclamation was not only the cornerstone of the Egyptian agricultural policy but it was also on the political agenda since the 1950s. It has been used as a remedy for a variety of problems e.g., desertification, alleviation of poverty, and reduction of graduate unemployment (Adriansen, 2009). The expansion in cultivation of non-traditional crops, especially in reclaimed land, has become one of the means of improving agricultural economic policy in the country. It usually concerns the shift of resources from low value agriculture to high value agriculture. It is not only a move from occasional and low value crop(s) to high value crop(s), but it could be considered also a need-based situation specific nonstop and vibrant idea, Hayami and Otsuka, (1992) commentated the issue. In the past few years, crop diversification played an essential role in the agricultural strategy of the country as aforesaid, and a diverse array of non-traditional crops has been cultivated. Hence, crop diversification can be recognized as a new driver of weed growth. Consequently, it is worth wondering about the ecological preference of weed growth in response to the presence of this new driver additionally to the drivers formerly mentioned, viz., crop diversification, crop seasonality and soil type; which is the topic of the present phytosociological study.

The differentiated ecological preference of species in **crop seasonality** was evident through the results of AHC, where the weed assemblages associated with agronomic winter crops were separated in WAG A (group *Sonchus oleraceus* – *Rumex dentatus*), the weed assemblages associated with agronomic summer crops in WAG B (group *Bassia indica* –*Cyperus rotundus*), and those of agronomic perennial crops and horticultural crops (orchards) in WAG C (group *Cynodon dactylon* – *Chenopodium murale*). Moreover, the chunks of agronomic perennial crops were separated in one clade from those of orchards in WAG C. The higher species richness that was recorded in orchards (S = 287 sp.), and in WAG A (S = 160 sp.) in relation to that scored in the WAG B (S = 103 sp.) and in the perennial agronomic crops (S = 32 sp.), was a consequence of the high number of winter annuals which were present in the crops of CGS typology in the northernmost part of Nile Delta where the area is subjected to heavy rain fall during winter and horticulture was widely recorded. The appearance of winter annuals in their ecological niche, matched to the presence of specific environmental conditions which related first with the plentiful of water resources that are mainly available in arid habitats through high ratios of rainfall (Mahgoub, 2019b), and in general the spatio-temporal dynamics of vegetation in arid and semi-arid regions are largely determined by water availability (Li et al., 2001). It is also conspicuous due to the higher heterogeneity in species composition that is observed between WAG C and WAG B (β = 0.357) when they are compared pairwise than between the WAG C and WAG A (β = 0.300). In comparable, the lower heterogeneity in species composition between WAG A and WAG B when they are compared pairwise is attributed to the lower number of winter annuals relative to the total number of shared species (Ws and Sw) which were recorded.

The ecological amplitude of species differs and species dominant in a group may be recorded with lower frequency within another group as well. Even though this happens very often, i.e., species recordings shared between the groups, something that was expected and accepted (Mahgoub, 2019a, 2019b), however the measurement of the phi coefficient (Φ) indicated the significant influence of crop seasonality. Out of the 150 most influential weeds, 61-species were faithful to WAG A, 45 to WAG B and 44 to WAG C, of these, 33-species had statistically significant joint fidelity to their specified groups (WAG A – C) at a level of significance of 0.05 (X^2**:** α = 0.05, P* > 3.841). The acute angles between the vectors of crop seasonality and CGS, and the obtuse angles between the its vector and that of FGS in the RDA triplot correlation signify that the impact of seasonality on growth preference of weeds colonizing crops cultivated in sites of typology CGS, is more prominent than on the weeds thriving in crops grown in sites of the second typology. The measurement of SS and Sb% also underlines the significance of the effect of seasonality, suggesting that ecological behavior of weeds is affected in various ways by crop seasonality. Out of the 150 species designated as the most influential weeds, 87-species confine their growth activity or exhibit their best performance during the winter season (W = 64-species & Ws = 23-species) while 44-species enumerated during the summer season (S = 27-species & Sw = 17-species) and 19-species were recorded all-the-year-round. The categories "W" and "S" include winter and summer counts respectively, while the of species of the two other categories, viz., "Ws" and "Sw" showed tangible growth in the corresponding other half of the year (spring and autumn) either in crops that are cultivated during early winter or in those of early summer, respectively. Even the remaining 19 of which general set of species which were designated as all-the-year-round-year weeds (A), their Sb% values (-26.1 to + 8.9) indicated that they showed a ± ecological preference for growth either in winter or summer cultivations, where 7-species of them flourished during the winter half while 12-species in the summer half of the year. The measurement of the seasonal bias percentage also revealed that 16-species of the winter weeds and 10-species of the summer weeds showed a seasonal bias of at least 25%. Moreover, the test of the statistical significance of the calculated absolute species turnover (βA; Whittaker, 1972) for data of presence - absence among the two seasons of the year (winter/summer) express the effect of seasonality on structure of the identified weed communities and it was statistically significant at $P < 0.05$. In addition, partitioning the variation in the response matrix (species records) indicated also that the partial linear effect of crop seasonality on the response data was greater than that of the other environmental variables under study (refer to Fig. 4).

This remarkable impact of crop seasonality is attributed to the effect of seasonal climatic changes on the germination and growth of weeds where crops are cultivated in their suitable agricultural seasons, and the success of weed(s) to associate with crop(s) under certain environmental conditions depends on their ecological amplitude. De facto, the relationship between vegetation and climate is absolute, each is entirely dependent on the other (Mahgoub, 2019a).

The significance of growth behavior of weeds in response to **crop diversification** depends on the extent of the likely association of certain weeds with certain crops. The growth preference of weeds in response to crop diversification can be investigated through several results. The expansion in crop diversification and the cultivation of non-traditional crops in reclaimed land seems to be the main reason for what was observed during RDA analysis of the higher relative impact of crop diversification and crop seasonality on the structure of weed communities associated with crops cultivated in CGS than that on the structure of those associated with crops on FGS. Moreover, the measurement of the coefficient of variation for the 150 most influential weeds reveals that 136 species scored C_v > 50%, 34 of which achieved a score of $C_v \geq$ 100%. These 34-species are the most affected by crop diversification, showing greater growth preference in 13 of the 30 agronomic and horticultural investigated crops.

Although herbicides are the dominant tool used in modern agriculture to control weeds, however it is not a complete solution to the complex challenge that weeds present (Harker, and O'Donovan, 2013). The overuse of herbicides has led to the rapid evolution of herbicide-resistant (HR) weeds (Beckie 2006; Powles and Qin, 2010; Egan et al. 2011). This situation resulted in ever-increasing populations of HR weeds especially those with multiple herbicide resistance which conducted weed researchers to develop management systems that are less dependent on herbicides (Powles and Matthews, 1992). Considering this point of view, the noticeable weed/crop interaction recorded in the present study can be used as a successful cultural control technique to aid in developing a sustainable weed management practice. The application of crop diversification plan in crop rotation technique considering the stacking of these crops with those in which other species thrived, can be taken seriously as an adequate weed controlling mechanism and will cause the strongest population reduction of the weeds most harmful.

The results of several researches confirm the potential success of this approach as a weed management practice. Lotz et al. (1991) confirm that the adoption of crop rotation is a sustainable and beneficial way of avoiding the herbicides, and usually crop rotation is preferred rather than monocropping technique. Additionally, Crop diversification involves the cultivation of traditional and non-traditional crops, and the influence of crop type in structure of weed communities was a discussion matter of several ecologists who have declared that the type of crop has significant effect on species composition and weed community structure (Holzner, 1978; Andersson and Milberg, 1998; Fried et al., 2008; Andreasen and Skovgaard, 2009; Mahgoub, 2017). Furthermore, the interactions between weeds and crops and the extent of their competition for the available natural resources (e.g., weed-weed competition, weed-crop competition and crop-weed competition) were studied by several researchers (Radosevich & Holt, 1984; Garrison et al., 2014; Swanton et al., 2015) and they revealed that vigorous crops and higher crop density may be important in reducing weed competition. They also indicated the importance of cultural control techniques and Garrison et al. (2014) mention that although more research is needed to fully understand the effects of crop stacking on other aspects of the system, such as insect pests and diseases, crop stacking has the potential to improve weed suppression, and more generally it is a novel, process-based approach that could likely be applied to other weed management practices, such as mowing and herbicide application, and which could involve mechanisms other than weed-weed competition. The weed-crop competition was also discussed by other researchers. Korres (2018) **i**n the book of Non-Chemical Weed Control (pp. 97:114) points out that Lemerle et al. (1995) and Angonin et al. (1996) report reduction of nitrogen, phosphorus and potassium concentrations in a range of cereal crops due to competition with species *Lolium rigidum* Gaudin, *Veronica hederifolia* L. and *Avena fatua* L., and it has been shown in other agronomy studies that some species such as *Stellaria media* (L.) Vill., *Chenopodium album* L., *Cirsium arvense* (L.) Scop. and *Elytrigia repens* (L.) Nevski bind less nitrogen than cereals (Jornsgard et al., 1996; Stupnicka-Rodzynkiewicz et al., 1996). On the performance of the species *C. album*, Qasem (1992) cites that *Chenopodium murale* L. strongly competes some other species under various conditions and had negative impact of on different crops. Qasem (1997) adds that it accumulates N, P, K and Mg better than associated vegetable crops and many other weeds it co-exists with under field conditions. Blackshaw et al. (2004) conclude that another factor that determines the outcome of competition for nutrients is the phenotypic plasticity of weeds (i.e., species-dependent) that enables them to utilize high nutrient levels by means of luxuriant growth. Based on their summary of invasiveness cited in the Invasive Species Compendium (CABI/ISC, 2021), *C. murale* and three other predominant weeds of WAG can be considered from the world's worst weeds. Holm et al. (1977) report *C. murale* as a widespread weed species in more than 43 countries, describe *Sonchus oleraceus* as the almost perfect 'designer weeds' for a community composition because they grow and flower quickly and produce copious wind- and bird-dispersed seeds that germinate quickly in large numbers and invade a wide variety of environments including many cropped areas; record *Cyperus rotundus* in more than 90 countries where it grows as a weed infesting at least 52 different crops and list *Cynodon dactylon* as a 'serious' or 'principal' weed in no less than 57 countries in which it invades crops of tropics, subtropics, and temperate regions.

It should be also pointed out that a sundry of cultural control researchers studied crop-weed competition and the use of some crops to smother weeds. In their textbook the Crafts and Robbins, 1975 cite various crops as suitable for suppressing or stopping weed growth (potential smother crops), noting that rotation of crops with those that kill weeds by choking them out can be a very effective method of weed control especially in relevance for crops grown for organic certification. Other researchers also indicate that legumes or other cover crops are sometimes used for smothering *Cynodon dactylon* since the weed does not tolerate deep shade and shading drastically affects both above- and below-ground growth, and the main non-chemical approaches to control *C. dactylon* are deep tillage and shading/smothering crops (Gould, 1951; Burton et al., 1959; McBee, and Holt, 1966; Schmidt and Blaser, 1969; Hart et al., 1970; Burton et al., 1988). Light seems to be essential for successful germination of *Sonchus oleraceus* thus burial in the soil or a vegetation cover can inhibit its seed germination leading at the same time in a high seedling mortality (Sheldon, 1974; Fenner, 1978; Hutchinson et al., 1984). There is also evidence that growth rates of *Chenopodium murale* exhibit severe reduction as a response to intraspecific competition, and that the reduced K level in the soil decreases its competitive ability (Qasem, 1997). *Cyperus rotundus* has low tolerance of shade, a property that can be exploited in controlling this weed through crops with dense canopies (Rambakudzibga, 1999). Field observations across the crops and the sites selected for the purpose of present study and the tabular technique for species records indicated that, in comparison with the other four predominant species, *Bassia indica* and *Rumex dentatus* show a negative correlation with perennial cover. This fact indicates that they favor sites with low diversity and prefer to occur in habitats with a little competition, consequently, the measures of cultural control by weed-smothering crops will also be effective.

However, to obtain a successful diversification plan the suitable crop should be chosen, but the cultivation of a certain crop type is a result of the existing available natural resources such as soil type, plentiful of water, prevailing climatic conditions, ecological amplitude of the crop, ...etc. (Mahgoub, 2019a). Several researchers deliberated the effect of soil structure on the types of crops grown. Ocumpaugh et al. (1991) declared that Calcareous soils can induce Fe-deficiency chlorosis in several forages including many forage legumes, and Hopkins et al. (2007) indicated the unfavorable physicochemical properties of alkaline soils, and report that the agriculture is limited to crops tolerant to surface waterlogging, and Rice cultivation is preferable, however the report of FAO (1999) announced that Taro (*Colocasia esculenta* (L.) Schott) can be grown in paddy fields where water is abundant. It is estimated that about 20% of arable land and 50% of cropland in the world are salt-affected areas (FAO, 2007), and the effect of saline soils on the type of crop cultivated debated the interest of several researchers (Marschner, 1995; Ayers and Westcot, 1976). Saline soils are mostly also sodic and crops vary widely as far as their tolerance to soil sodicity. Gude (2018) indicated the adverse impact of the increase in $Na^{\pm}$ concentration on the soil's physical properties, and Abrol and Bhumbla (1979) report long-term field studies evaluating the effect of exchangeable sodium on the performance of several field crops: e.g., rice, sugar beet (tolerant); wheat, clover, sugarcane, cotton (semi-tolerant); and maize, lentil, cowpeas, peas, peanut (sensitive). Moreover, West Gippsland Catchment Management Authority (WGCMA) in its annual report 2018–19 reveals that most sodic soils can be ameliorated by a low capital input investment, considering that through phytoremediation and a crop diversification plan which will be based on cultivation of deep rooting plants (e.g., lucerne, tillage radish and canola) soil improvement and productivity growth could be achieved. They also declared that *Brassica* crops stimulate soil mineral N accumulation, and maintaining lucerne (*Medicago sativa* L.) as an under crop minimize in-crop nitrogen requirements and provide maximum ground cover in a mixed farming system and fill feed gaps.

Among the abiotic factors, topography, and soil type play a major role in the heterogeneity of habitats, thus contributing to physiognomic differentiation of vegetation (Oliveira-Filho and Ratter, 2002; Baldeck et al., 2013; Guerra et al. 2013). The diversified growth preference of weeds in response to **soil type** and other physical soil properties influenced by its texture (e.g., porosity, permeability, infiltration, shrink-swell rate, water-holding capacity, and susceptibility to erosion) is clearly reflected in the results of the present study. ISA illustrates that out of the 150 most influential weeds, 66-species have growth preference in FGS and 84-species in CGS soils (refer to synoptic table - Appendix 1). The analysis also certifies that 94-species of them scored an *INDVAL* of at least 25% in one of the two identified site typologies, and 29-species of them can be characterized as strong indicators for a specific environmental condition (ecological niche). Although the influence of soil type on weeds preference for growth was evident during the RDA, results from ecological and agricultural researches recommended the use of the soil physicochemical properties as supplementary variables. A sundry of them reveals the effect of soil texture as well as of other physical soil properties influenced by it, on vegetation structure. Sparks (2003) concluded that soil structure, or the arrangement of soil particles, has a critical effect on permeability and infiltration. Passioura (1991) declare that the soil structure, the spatial arrangement of its individual particles and their aggregates, and its pores, play a multifaceted key role in the factors determining crop and vegetation performance. Lane et al. (1998), Le HouŽrou (1984), and Sala et al. (1988) discuss that soil texture has on the above-ground net primary production of plant communities (ANPP). Parton et al. (1987, 1993) and Burke et al. (1989) indicate that soil texture may also exert a control on nutrient availability, and that fine-textured soils have higher levels of organic matter and greater nutrient availability than coarse-textured soils. Moreover, the effect of soil chemical properties on weed community composition, weed density, and soil fertility are also a matter of discussion in several ecological and agronomic researches. Andreasen et al. (1991) and Otto et al. (2007) reveal a relation between the density of some weeds and the existence of certain soil characteristics. Ayers and Westcot (1976) and Marschner (1995) discuss the sensitivity or tolerance of species to salts and indicate the adverse effect of increasing soil salinity. Gregorich et al. (1994) declare that the soil organic matter (SOM) is important in maintaining several soil properties and Oates (2008) indicates that the addition of $CaCo_3$ in the form of agricultural lime (ag lime) affects soil pH and soil nutrient availability. Saline soils are mostly also sodic and several researchers report that salinity and sodicity have a major effect on the structure of soils consequently affecting both physical and chemical fertility of them (Abu-Shara et al., 1987; Goldberg et al., 1988; Tajik et al., 2003; Shainberg et al., 1992). In light with these findings and from the present results also becomes clear that the optimal growth of a species is related to both the physical and chemical properties of the soil. Hence, during RDA soil chemical properties were taken into consideration as supplementary variables for soil type interpretation. The results reveal that four of the predominant species in the identified WAG (*Chenopodium murale*, *Sonchus oleraceus*, *Rumex dentatus* and *Cyperus rotundus*) showed a higher probability of occurrence (i.e., predicted relative frequency) in FGS sites of Nile Delta characterized by high soil content of K, high capacity of water holding and low soil salinity, while the other two (*Cynodon dactylon* and *Bassia indica*) showed their maximum growth preference in CGS sites of east and west territories of Nile Delta characterized by high soil salinity and low water holding capacity. Additionally, the ordination of the species objects constituting the identified alliances (within-group associations) in the RDA correlation triplot reveal that the probability of occurrence of alliances is correlated to the presence of certain site typology accompanied with specific soil chemical properties as well: A9 is prevalent in sodic soil; A6 in alkali soil; A7 in calcareous soils; A8, A11, A12 in soil characterized by high soil salinity; A3, A4, A5, A10 in soil with high content of HCO_3; A1, A2, in soil with high content of K. The variability in the values of diversity indices for these alliances and the statistical significance of their similarity in floristic composition (*J*) which are observed in the results of the current study in addition to the observed variation in the diversity of vegetation units (WAG) emphasize the effect of both physical and chemical properties of soil on the performance of species which mainly depends on the phenotypic plasticity and ecological amplitude.

The findings of several studies focusing on the ecology of weeds coincide with the results of the present study in several points either. To name few of them: Hutchinson et al. (1984) reported that *Sonchus oleraceus* is found on many different substrates, including saline soils, but never on acid peat, and it primarily occurs on relatively moist soils, rich in sodium, phosphorus, potassium, and calcium; Qasem (1992) mention that *Chenopodium murale* has been regarded as a nutrient accumulator with a high demand for K and N; Hussain et al. (1997) suggest that *Rumex dentatus* grows in disturbed habitats, often in moist areas, such as lakeshores, edges of cultivated fields, and has allelopathic activity; Bhati et al. (1979), and Bendixen & Nandihalli (1987) declare that *Cyperus rotundus* may be found growing in soil types heavy clay of varying salinity and that the purple nutsedge (*C. rotundus*) grows best where soil moisture is high such as in Rice and Sugarcane culture, and consequently it is not an important weed of arid regions except on irrigated land; Holm et al. (1977) notify that *Cynodon dactylon* occurs under semi-arid and irrigated conditions on a wide range of soil types of varying pH and added that the undisturbed rhizome system of Bermuda grass can survive flood conditions and drought but it favors the growth in the medium-to-heavy moist well-drained soils; and Shaltout and El-Beheiry (2000), and Hand (2003) report that *Bassia indica* grows in saline soils providing a dense cover for the soil surface, and thus aids soil conservation and management and Hashem et al. (2016) added that this species is adapted to abiotic stress and has been used in the repair of desert ecosystems, in salt phytoremediation and for livestock grazing on land affected by salinity, it is an annual halophyte that mainly occurs in desert ecosystems and can be found in salt marshes; Cal-IPC (2004) indicates that *Brassica nigra* is a weed appearing after disturbance events and it can be found wild growing in a variety of plant communities in regions with high soil moisture, and while colonizes many soils except those of heavy clays, black mustard (*B. nigra*) grows best on light sandy loams or deep rich fertile soils; Maun and Barrett (1986) declared that *Echinochloa crus-galli*, prefers open sunny places and is largely restricted to wet soils, from loamy to clay. It can tolerate drier soils, but can also continue to grow when partially submerged and *E. crus-galli* growing in wetland rice fields was unaffected by submergence under 90 cm of natural floodwater for up to 40 days; Holm et al. (1977), and Santoso et al. (1996) indicate that the habitats of *Imperata cylindrica* vary from dry sand dunes of shores and deserts to swamps, cultivated annual crops and river margins and is widely believed to indicate poor soil fertility; Thanos et al. (1991) and Minnich & Sanders (2000), report that *Brassica tournefortii* inhabits sandy coastlines typically along the Mediterranean coastline, its native habitat is typically areas of wind-blown, sandy arid, or semi-arid environments.

It is eminent from the results that the developmental preferences of weeds and the subsequent diversity of communities that they form within the cultivated crop(s) are a consequence of their response to the combined effect of crop diversification, crop seasonality, and soil type. This assumption is confirmed by correlating the results of the analyzes conducted with each other (AHC, ISA, Fr/Ab, SS, Sb%, RDA, VP), considering the measured diversity indices and coefficients (S, H, E, D, C_v, J, Φ), along with the ordination of species objects in RDA correlation triplot (proximity between species points, and the distances between species/sites objects/variable's vector, X^2 distance). For example, grouping of the recognized associations within three WAG groups (A – C), which correspond to three different types of agroecosystems is the result of the differential response of the six predominant species to three environmental variables (diversification/seasonality of crops and soil type) which is usually attributed to the plant species phenotypic plasticity and heterogeneity (Shaltout & Sharaf El-Din, 1988). However, some species thrive well at the same soil conditions (Ellenberg et al., 1992), and the increase of convergent ecological conditions between sampling areas, affects their floristic composition which depends on the species phenotypic plasticity (Mahgoub, 2019a).

5. Conclusion

It is perspicuous that growth preference (selective development, growth behavior) of weeds is a result of their response to the combined effect of the three environmental variables under study: crop diversification, crop seasonality, and soil type. Three weed assemblage groups (WAG) were distinguished associated with the 30 agroecosystems monitored. In these three different types of agroecosystems, 12 alliances (associations within-WAG groups) and 29 strong indicator species were recognized, the maximum ecological success of which matches to a specific environmental condition (ecological niche). Although weed control is a recalcitrant issue, however the results indicated that a portion of the solution is in a successful plan of crop-diversification. The successful selection for a competitive crop that can be taken seriously as an adequate weed controlling mechanism in a crop rotation technique inevitably will cause strong population reduction of harmful weeds on infested farmland improving soil productivity and increasing crop yield.

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sjbs.2021.05.070.

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