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Changes in weed species composition in irrigated agriculture in Saharan Algeria

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Summary

This work characterizes the changes in composition of the weed flora commonly associated with certain southeastern Algerian crops over a twenty-year period. Vegetation sampling was carried out between 1990 and 2010 in three one-hectare date palm plantations that do not have understory crops, six 400-m² greenhouses used for market gardening, and three 30-ha cereal center-pivot irrigation plots. In total, 162 species belonging to 40 families were recorded. As in many other agroecosystems around the world, the dominant families are *Poaceae*, *Asteraceae*, *Brassicaceae* and *Amaranthaceae* representing 45.1% of the species identified. The weed communities were characterized by a set of species from various origins: species with biregional, triregional, and multiregional origins, Saharo-Arabian and Mediterranean species were particularly well represented. Overall, the most common weed species were: *Chenopodium murale*, *Lolium multiflorum*, *Melilotus indicus*, *Lysimachia arvensis*, *Sonchus oleraceus*, *Setaria verticillata*, *Polypogon monspeliensis* and *Erigeron canadensis*, all of which are therophytes. The weed flora differed among the three sampled agroecosystems, which is to be expected, as their respective management sequences are quite different. Weed monitoring over the 20 years showed that weed composition changed overtime, particularly in the palm plantations and the cereal plots. For a better understanding of the drivers of weed composition and changes over time and better weed management, studying weed provenance (crop seed purchase, and organic fertilization) as well as agricultural practices is necessary.

Keywords: agroecosystems, camel rangeland, cereal center-pivot irrigation plots, date palm plantations, greenhouses, market gardening

Introduction

Global changes influence weed distribution, species dominance, and other aspects of weed communities in agroecosystems (e.g. climate change: Zicka and Dukes, 2011). Changes in agricultural practices associated with intensified crop production are by far the leading root cause of weed dynamics: this follows directly from the ecological implications of increased seeding and planting, increased fertilizer and pesticide use, and simplified crop rotation (Kleijn *et al.*, 2009). On the one hand, the difficulty in controlling weeds is one of the major reasons for which farmers are forced to relinquish cultivated plots and to plow new ones; on the other hand, some weed control practices have proven detrimental to many of the plant and animal communities that are associated with agricultural environments (Flohre *et al.*, 2011) while weeds can play an important role in supporting diversity for higher trophic levels (Marshall *et al.*, 2003). Whereas these changes occur on weed communities, a thorough knowledge of the composition of weeds, along with their spatial and temporal distribution, is a prerequisite for good weed management in agroecosystems.

In Algeria, several studies have increased our understanding of the composition and distribution of weed flora in various northern regions of the country, with a Mediterranean climate, such as: on the Mediterranean central coast (Chevassut *et al.*, 1988; Boulfekhar, 1989; Fenni, 1991; Abdelkrim, 1995), and on the Mediterranean north-eastern Algeria (Fenni, 1991) and north-western Algeria (Kazi Tani *et al.*, 2012) coast. However, many agricultural regions of the country remain under-characterized.

Indeed, there currently exist no studies on the weed flora of the Saharan Algeria. Algeria has a flora comprising about 3139 species, of which 653 species (accounting for 12.6% of the total number of species) are endemic and distributed among nearly 150 families. Among the endemic flora, more than 25% of the species are associated with crops (Quézel & Santa, 1962-1963). Botanical and plant ecology studies in the Sahara regions are scarce and mainly oriented towards the native flora of natural areas, such as that of camel rangelands (Ozenda, 2004; Chehma *et al.*, 2008) and conservation and narrow endemic species (Brito *et al.*, 2013; Migliore *et al.*, 2013).

Our present work aims to show whether the composition of the weed flora associated with irrigated crops in southeastern Saharan Algeria has changed over a period of twenty years from 1990 to 2010. We studied a set of cereal fields, greenhouses and palm plantations. We hypothesized that the weed flora of cereal fields and palm plantations would change little over the study period because cereal cultivation practices are unchanged since the 1980's and

interventions are relatively minor in palm plantations after their establishment. We expected more changes in greenhouses where practices potentially evolve more rapidly.

Materials and Methods

Study area

The study was conducted in Hassi Benabdellah, located in northeastern part of Saharan Algeria, about 800 km from Algiers (32°01'N; 5°28'E; Fig. 1). The northern Sahara, which covers an area of 1 million km², receives precipitation in the winter and yields 100±50 mm of rainfall per year (Hamdi-Aissa et al., 2004). It is essentially a transition zone between the northern African Mediterranean steppes and the central Sahara desert, and it was selected mainly for its agricultural potential. Indeed, many important crops, such as dates, greenhouse gardens, and cereals grown using center-pivot irrigation (sometimes called central pivot irrigation or circle irrigation), are all farmed in this region. A relatively recent import to the area, intensive crop cultivation, first appeared in the region in the late 1960s and early 1970s, mainly occupying what had once been open camel rangeland. Although irrigation is applied all year long in the date palm plantations (surface irrigation; once a week from November to March and 2 to 3 times a week the rest of the year), it is only applied during the growing season on cereal plots (center pivot irrigation; 866 mm/m²) and market gardening greenhouses (surface irrigation; twice a week from November to February and 3 times a week from March to May). None of the plots selected for this study were treated with herbicides.

Sampling method

The present study covers the twenty-year period beginning in 1990, and handles the full twenty years in two stages. The first stage relies on a synthesis of all the data from previous studies mentioning exhaustive weed flora sampling in the ITCMI (Institut Technique des Cultures Maraichères et Industrielles) and ITDAS (Institut Technique de Développement de l'Agriculture Saharienne) research stations between 1990 and 2002. For that period, one presence-absence plant list was compiled per year surveyed per crop type (Table 1; ITCMI & ITDAS, 2002). The second stage of the analysis, covering the period from October 2003 to June 2010, is based on weed surveys conducted by the authors according to the following protocol. For both stages, to match the seasonal planting and harvest schedule, surveys were carried out starting in October of each year (x), and repeated in February and June of the following year (x + 1), to give a total of three surveys per year. The data from each set of three surveys were then taken together to fully characterize each October x to June x+1 crop

year. We used the Base de données des plantes d'Afrique for plant nomenclature (CJB & SANBI, 2014). The botanical attributions for weed species are listed in Appendix 1 in Supplementary Material.

Sampling in cereal plots

Three 30-ha cereal center-pivot irrigation plots, hereafter referred to as cereal plots, cultivated with either hard (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.) or soft (*Triticum aestivum* L. subsp. *aestivum*) wheat, were selected. These plots started to be cultivated in the mid 1980's. In each cereal plot, three 100m-long and 2m-wide transects were randomly placed and sampled by establishing a presence-absence plant list three times per year between wheat seeding and harvesting. The three samples taken on the same transect year were pooled for analysis ($n = 63$; $6 \text{ sites} \times 3 \text{ transects} \times 7 \text{ years}$). The pre-2003 data, collected over 8 years, were considered together with the post-2003 data in the multivariate analyses (with $n = 63 + 8 = 71$).

Sampling in market gardening greenhouses

Six 400-m² greenhouses, cultivated since the early 1980's, were selected. In each greenhouse, three 50m-long and 1m-wide transects were randomly placed and sampled by establishing a presence-absence plant list three times per year, although the exact time of year at which sampling occurred varied according to crop type (and therefore crop cycle). The three samples taken within the transect year were pooled for analysis ($n = 126$; $6 \text{ sites} \times 3 \text{ transects} \times 7 \text{ years}$). The pre-2003 data, which came from for 13 years (Table 1), were considered together with the post-2003 data in the multivariate analyses (with $n = 126 + 13 = 139$).

Sampling in date palm plantations

For the palm cultivation portion of the study, three one-hectare date palm (*Phoenix dactylifera* L.) plantations without understory crops were selected. These plantations had been established in 1972. In each plantation, three 100m-long and 10m-wide parallel transects were randomly placed and sampled by establishing a presence-absence plant list three times per year. The three samples taken on the same transect from October in the year x to June in the year $x+1$ were pooled for analysis. This means that a given crop year was statistically characterized by a total of $3 \text{ sites} \times 3 \text{ transects} \times 7 \text{ years}$, $n = 63$). The pre-2003 samples consist of data collected over 9 years (Table 1), and are considered in the

multivariate analyses (with $n=72$, following from $9 + 63 = 72$) in which the pre-2003 and post-2003 datasets are handled together.

Plant species study

In order to analyze the characteristics of the species found on the various plots, all species were classified according to (1) their family; (2) their chorotype and (3) their life-form according to Raunkiaer's life form using the following floras: Quézel & Santa (1962-1963), Ozenda (2004), Tison & de Foucault (2014) and Danin (2015) (see Appendix 1 in Supplementary Material). The chorotypes were simplified in 7 categories: 1. Alien species from Americas, Australia and South Africa, 2. A complex chorotype containing species with biregional, triregional, and multiregional origins, 3. Euro-Siberian (ES), 4. Irano-Turanian *stricto sensu* (IT), 5. Mediterranean *stricto sensu* (M), 6. Saharo-Arabian *stricto sensu* (SA), and 7. Sudanian (S).

Data analysis

We analyzed differences in percentages of weed species / transect for each crop type separately, depending on the explanatory variable "chorotypes" (or "life forms") using generalized linear models with binomial error distribution. When the explanatory variable was significant, we conducted pairwise comparisons with Tukey's pairwise comparison tests using function 'glht' in the package "multcomp" in R (R Core Team 2018). For all tests, P-values lower than 0.05 were considered as statistically significant.

We analyzed differences in number of weed species / transect along time for each crop types separately. Two Mixed-effects Generalized Linear Models were compared for each crop type: one with "years" as an explanatory variable and one without. For these analyses, only the data from 2003 to 2010 were used. If the first model had a lower AIC (Akaike Information Criterion), time was considered as having a significant effect and we conducted pairwise comparisons with Tukey's pairwise comparison tests using function 'glht' in the package "multcomp" in R (R Core Team 2018). The same procedure was carried out to assess the differences in percentages of weed species / transect along time for particular chorotypes or life forms, considering crop types separately.

The relationships between explanatory variables (crop types or years) and weed assemblages were explored using Correspondence Analyses (CA). To describe the vegetation corresponding to each crop type, a first CA was run on all vegetation surveys (282 samples $\times$ 169 species). Then, to describe the changes in weed composition for each crop, three separate

CAs were run 1) on the palm plantation samples (72 points $\times$ 123 species), 2) on the cereal plot samples (71 points $\times$ 110 species) and 3) on the greenhouse samples (139 points $\times$ 32 species). These analyses were followed by a Multiple Response Permutation Procedure analysis (MRPP) to determine the statistical significance between the crop types or the years. On the figures, for clarity, only the species the most correlated to axes 1 and 2 are shown. All of the analyses were conducted with R 3.4.4 (R Core Team 2018), univariate analyses with its package “lme4” and “multcomp” and multivariate analyses with its packages “ade4” and “vegan”.

Results

Weed composition depending on crop types

The number of weed species varied from 119 species in the palm plantations (9000 m² explored every year) to 104 in cereal plots (1800 m² explored every year) and 31 species in greenhouses (900 m² explored every year). In total, during the two sampling periods (1990-2002 and 2003-2010), we identified 162 weed species from 40 botanical families, three of which made up for almost half of the species in the study (45.1% of the species): *Poaceae* (20.4%), *Asteraceae* (14.2%) and *Brassicaceae* (10.5%) of the species. *Poaceae* (19.2%, 35.5% and 22.7% of the weed species in cereal plots, greenhouses and palm plantation respectively), *Asteraceae* (18.7%, 16.1%, 14.3%) were the dominant families in all crop types. The third most represented family was *Brassicaceae* in cereal plots (14.4% of the species). In greenhouses and palm plantations *Amaranthaceae* was the third most represented family (12.9% and 7.6% respectively) (see Appendix 1 in Supplementary Material).

The MRPP analysis, as run on all the samples, showed a significant difference in weed species composition between the crop types (observed delta: 0.37; expected delta: 0.60; p-value<0.001). The first two first axes of the CA explained 31.0% of the total inertia. As shown in Fig. 4, axis 1 (16.4%) delineated cereal plot samples correlated with *Anisantha madritensis*, *Avena barbata*, *Daucus carota*, *Emex spinosa*, *Fagonia glutinosa*, *Launaea capitata*, *Raphanus raphanistrum*, *Sinapis arvensis*, and *Trigonella polycerata*, from greenhouse samples correlated with *Amaranthus retroflexus*, *Convolvulus arvensis*, *Cynodon dactylon*, *Cyperus rotundus*, *Digitaria nodosa* and *Senecio vulgaris* (Fig. 4; the botanical attributions for weed species are listed in Appendix 1 in Supplementary Material). Axis 2 (14.6%) separated these samples from the palm tree plantation samples correlated with *Cressa cretica*, *Tamarix gallica*, *Juncus maritimus*, *Euphorbia chamaecyse*, *Sonchus maritimus*, and *Phragmites australis* (Fig. 2).

Weed chorotypes and life-forms depending on crop types

The study area, located in the northeastern part of Saharan Algeria, was characterized by a set of species from various origins. Overall, 47% of the species belong to the complex chorotype, 25% are Saharo-Arabian species and 18% are Mediterranean species. The other categories (Alien, Euro-Siberian, Irano-Turanian, Saharo-Arabian and Sudanian) accounted for 10% of the species. The most common weed species on the three crop types were: *Chenopodium murale*, *Lolium multiflorum*, *Melilotus indicus*, *Lysimachia arvensis*, *Sonchus oleraceus*, *Setaria verticillata*, *Polypogon monspeliensis* and *Erigeron canadensis*, all of which are therophytes. Five of them belong to the complex chorotype (*Chenopodium murale*, *Lysimachia arvensis*, *Polypogon monspeliensis*, *Setaria verticillata*, *Sonchus oleraceus*), two are Mediterranean (*Lolium multiflorum*, *Melilotus indicus*), and one is an alien species from America (*Erigeron canadensis*).

In all three crop types, the most common chorotype category was the complex chorotype (Fig. 3). The second most common chorotype category in the cereal plots was Mediterranean (e.g. *Lolium multiflorum*, *Avena barbata*, *Melilotus indicus*, *Sinapis arvensis*), while it was Aliens (e.g. *Erigeron canadensis*, *Cyperus rotundus*) in the greenhouses and Saharo-Arabian (e.g. *Moltkiopsis ciliate*, *Ifloga spicata*, *Launaea capitate*, *Tetraena alba*) in the palm plantations (Fig. 3).

Overall, 'therophytes' was the most represented life-form (Fig. 4). Palm plantations were the crop type with the greatest diversity of life-forms, including perennials and a significant amount of hemicryptophytes (Fig. 4; Appendix 1 in Supplementary Material). Few species were geophytes and perennials, mainly found in the palm plantation. More than 60% of the species exhibiting a Mediterranean range or belonging to our complex chorotype category were therophytes. This life-form represented less than 50% of the species with a Saharo-Arabian range, while other species with this origin mainly belonged to chamaephytes or hemicryptophytes (only one geophyte: *Euphorbia guyoniana*).

Weed species richness changes with time

The number of weed species in cereal plots tended to decrease from 1990 to 2003 and then significantly increased from 2003 to 2010 ($df=6$, $F=22.01$, $p\text{-value}<0.001$). In greenhouses, the number of weed species tended to be constant around 18.1 ± 0.6 weed species / transect from 1990 to 2010, with a few punctual increases (e.g. in 2004-05: 22.4 ± 1.2 ; $df=6$, $F=5.21$,

p-value<0.001). The number of weed species in palm plantations tended to increase from 1990 to 2003 and then stabilized around 52.3 ± 3.0 weed species / transect (df=6, F=1.42, p-value=0.224) (Fig. 5).

Weed chorotypes and life-forms changes with time

Significant variations of percentages of therophytes were observed in the greenhouses, with no specific trends (Table 2). Variations of percentages of therophytes in the cereals plots and of therophytes and hemicryptophytes in the palm plantations were not significant.

Significant variations of percentages of species in the complex chorotype category were observed in the cereal plots and in greenhouses, with no specific trends (Table 2; Fig. 6). Percentages of alien species significantly increased in the greenhouses, while percentages of Saharo-Arabian species decreased in the palm plantations (Table 2; Fig. 6).

Weed composition changes with time

The CA, as run on cereal plot data, showed a clear change in species composition with time and this was confirmed by the MRPP analysis showing a significant difference between the dates (observed delta: 0.17; expected delta: 0.37; p-value<0.001); the first two first axes of the CA were found to explain 37.6% of the total inertia. As shown in Fig. 7, axis 1 (23.9%) delineated old samples (1990-2000) correlated with *Ammosperma cinereum*, *Atractylis delicatula*, *Brocchia cinerea*, *Diploaxis acris*, *Launaea mucronata*, *Malcolmia africana* and *Paronychia arabica* from other samples (Fig. 7). Axis 2 (13.7%) separated the samples gathered between 2003 and 2005, correlated with *Callipeltis cucullaris*, *Lysimachia arvensis* and *Rostraria cristata* from the more recent samples (2008 to 2010) correlated with *Calendula arvensis*, *Frankenia pulverulenta*, *Galium tricornutum*, *Henophyton deserti*, *Papaver rhoeas*, *Scandix pecten-veneris*, *Sonchus asper*, *Stipagrostis obtusa* and *Tetraena alba* (Fig. 7).

The CA, as run on the greenhouse data, only showed that some years (1990-91, 2004-05, 2006-07) were different from others (Fig. 8) and this was confirmed by the MRPP analysis showing a significant difference between the dates (observed delta: 0.22; expected delta: 0.30; p-value<0.001); the first two first axes of the CA were found to explain 32.2% of the total inertia. Axis 1 (17.1%) delineated the 2004-05 samples, correlated with *Dactyloctenium aegyptium* and *Solanum nigrum*, from the samples from other years. Axis 2 (15.1%) distinguished the oldest samples (1990-1991) correlated with *Cutandia dichotoma* and *Spergularia marina* (Fig. 8).

The CA, as run on the palm tree plantation data, also showed a clear change in species composition with time and this was confirmed by the MRPP analysis showing a significant difference between the dates (observed delta: 0.37; expected delta: 0.49; p-value<0.001); the first two first axes of the CA (axis 1: 16.6% and axis 2: 11.3%) explained 27.9% of the total inertia. As shown in Fig. 9, *Agathophora alopecuroides* and *Stipagrostis plumosa* were mainly found in the early years, followed by *Anethum graveolens* and *Echium pycnanthum* at the end of the 1990's and by *Glaucium corniculatum* and *Ogastemma pusillum* the start of the 21st century. Around the late 2000's, *Cressa cretica*, *Cyperus rotundus*, *Phragmites australis* *Tamarix* sp. became more common (Fig. 9).

Discussion

Overall weed composition

The three most common families encountered in this study, namely *Poaceae*, *Brassicaceae* and *Asteraceae* were such a dominating presence because they are important families of the Algerian flora, especially in the Sahara (Ozenda, 2004), and they are adapted to disturbed environments (Holm *et al.*, 1977; Taleb & Maillet, 1994). Indeed, Holm *et al.* (1977) report that *Poaceae*, *Cyperaceae*, *Asteraceae*, *Polygonaceae*, *Amarantaceae*, *Brassicaceae* and *Fabaceae* constitute the major crop weed families. Other studies in semi-arid Mediterranean and tropical environments have also shown that *Amarantaceae*, *Asteraceae*, *Brassicaceae*, *Fabaceae*, *Poaceae*, *Polygonaceae*, and *Solanaceae* are very common in the vegetation and seed bank (Dorado *et al.*, 1999; Salama *et al.*, 2016). Our results are also comparable to those reported by studies in Mediterranean Algeria (Boulfekhar, 1989), Morocco (Bouhache *et al.*, 1994) and Egypt (Salama *et al.*, 2016). The most common weed species recorded in this study (*Chenopodium murale*, *Lolium multiflorum*, *Melilotus indicus*, *Lysimachia arvensis*, *Sonchus oleraceus*, *Setaria verticillata*, *Polypogon monspeliensis* and *Erigeron canadensis*) are recognized as major weeds elsewhere in the world (e.g. USDA, NRCS 2015), with their status as invasive depending on the region considered. *Chenopodium murale*, *Melilotus indicus*, *Sonchus oleraceus* and *Polypogon monspeliensis* were also found to be dominant weed species in wheat, millet or alfa-alfa fields studied by Salama *et al.* (2016).

The proportion of weeds exhibiting Mediterranean or Saharan ranges was high, accounting for 43% of the species, but 47% of the weeds belong to our complex chorotype category, with biregional, triregional, and multiregional origins. According to Ozenda (2004), the flora of northern Sahara is characterized by a preponderance of the Saharan species with only some incursions of Mediterranean species. This apparent disparity between our

observations and Ozenda's prediction can probably be explained by habitat differences. Ozenda described the flora of all Saharan habitats, including e.g. camel rangelands which experience recurrent disturbances due mainly to drought and grazing and which are thus characterized by an adapted Saharan flora. On the other hand our study was conducted in agroecosystems which are highly disturbed environments. Cultivated fields represent a particular kind of artificial ecosystem that is subject to tillage, pesticides, fertilizers, irrigation and other interventions, thus experiencing an exceptional frequency and intensity of disturbances intended to maintain favorable conditions for production (Smith, 1995). Artificial watering, in particular, provide conditions favorable to Mediterranean species (Steinmaus & Norris, 2002). These disturbances lead to a banalization of the weed flora (Kazi Tani *et al.*, 2012) and a depletion of endemic species in this type of environment (Jauzein, 2001). With the Mediterranean and complex chorotype species being mainly therophytes (over 60%), these provenances create a dominant therophytic component in the Saharan weed assemblage.

Differences in weed composition between crop types

The weed flora is mainly related to soil and climatic conditions, but also varies in composition and number of weed species depending on crop types and the agricultural practices associated with these crops (Zimdahl, 2013; Salama *et al.*, 2016). These differences are explained by the differences in crop management sequence, particularly where it concerns tillage. In greenhouses, tillage occurs continuously throughout the growing season, as part of incorporating mineral fertilizers, weeding, and hoeing (to aerate the soil). In addition, greenhouse crops (*Solanaceae*, *Cucurbitaceae*, *Fabaceae*) offer more possibilities for rotation compared to the two other crop types, which are limited to a single botanical family (*Poaceae* in cereal plots and *Arecaceae* in palm plantations). Greenhouse crops therefore have a greater diversity of agricultural practices, and this can explain their relatively low number of weed species (Pyšek *et al.*, 2005; Armengot *et al.*, 2011). It can also explain the presence of *Amaranthus retroflexus*, *Chenopodium murale* and *Senecio vulgaris*, which have a very rapid life cycle. Ball (1992) also reports that in irrigated market gardening crops, tillage and crop rotation are the main factors explaining the floristic composition of weeds and the seed bank, which in turn explain the number of weed species of the vegetation in the plot.

In the cereal plots, tillage only occurs once a year at the time of crop establishment (tillage + sowing) in the fall (October). This provides time for Saharan species from the

surroundings camel rangelands to colonize the cereal plots: e.g. *Atractylis delicatula*, *Carthamus eriocephalus*, *Ifloga spicata*, and several species of *Launaea*. The cereal plots are characterized by a second group of weed species, of Mediterranean origin, probably sowed with wheat seeds (Tanji & Taleb, 1997): e.g. *Avena barbata*, *Daucus carota*, *Emex spinosa*, *Raphanus raphanistrum*, *Sinapis arvensis*, and *Trigonella polycerata*.

In palm plantations without understory crops, tillage is limited to a single hydro-agricultural development at the time of tree planting in which ditches are created to ensure irrigation of the date palms (Zaid, 2002). Once the plantation is established, the soil is not tilled anymore. Palm plantations are thus characterized by perennial species: chamaephytes (*Cynodon dactylon*), geophytes (*Cyperus rotundus*, *Cressa cretica*, *Colchicum gramineum*, *Oxalis pes-caprae*), hemicryptophytes (*Phragmites australis*, *Erodium glaucophyllum*, *Juncus maritimus*, *Sonchus maritimus*), and phanerophytes (*Tamarix gallica*). They are also characterized by weed species that prefer moist soil and can tolerate salt, such as *Cressa cretica*, *Euphorbia chamaecyze*, and *Sonchus maritimus*. Salt is a result of the high evaporation rate characterizing arid and semiarid climates, an effect that causes salt to accumulate in the top layer of the soil (Al-Amoud, 2010). It can also come from irrigation with marginal groundwater resources and from a rise in the water table (Bouarfa *et al.*, 2009).

Changes in weed composition over time

In cereal plots, old samples are characterized by species found on the camel rangelands of the region, such as *Ammosperma cinereum*, *Atractylis delicatula*, *Brochia cinerea*, *Diploaxis acris*, *Launaea mucronata*, *Malcolmia africana*, *Malva aegyptia* and *Paronychia arabica*. With time, a mix of weeds (e.g. *Sonchus asper*) and segetal species (e.g. *Papaver rhoeas*, *Galium tricornutum*, and *Scandix pecten-veneris*) colonized these plots. These species are probably sown with the wheat seeds coming from the northern part of the country as has been shown to occur in Morocco (Tanji & Taleb, 1997). While some species native to the camel rangelands progressively disappear from the cereal plots (*Atractylis delicatula*, *Carduus getulus*, *Cornulaca monacantha*, *Paronychia arabica*, and *Sisymbrium reboudianum*) others manage to maintain themselves (e.g. *Henophyton deserti* and *Tetraena alba*), although species of both groups belong to various life-forms (chamaephytes, hemicryptophytes and therophytes). On the other hand, a study run from 1985 to 2005 in southern Spain showed that weed diversity did not change over time (Hernandez Plaza *et al.*, 2011). This might be explained by the fact that the fields had been cultivated with wheat for 10 years prior to the

start of the study. This is unlike our own study, initiated just a few years after the start of cultivation in the mid 1980's. In order to better understand the drivers of change on the cereal plots, a thorough survey among farmers would need to investigate wheat seed provenances and changes in practices that might have gone unnoticed. A study of the species sown along with wheat seeds would also be useful, but might not to be feasible as one would need samples from seeds sown from 1990 to 2010. Finally, a seed bank study in cereal plots of various ages would provide information on native rangeland species depletion.

In the early years, indigenous species were already scarce in greenhouses which is probably due to the fact that these plots had been cultivated for 10 years before the start of the study. This crop type also induce the most disturbances of the three studied crop types. This and the frequent crop rotations (*Solanaceae*, *Cucurbitaceae*, *Fabaceae*) most probably explain the lack of patterns of weed communities through time. Indeed, the weed flora has not changed much in greenhouses over the last twenty years and is characterized by anthropophilous or widespread species (e.g., *Amarantus retroflexus*, *Chenopodium murale*, *Erigeron canadensis*, and *Sonchus oleraceus*) probably sown with crop seeds. Indeed, crop seeds are often bought from the northern part of the country and are not pure. Studying the species sown along with crop seeds would be useful to better understand weed species composition. A fertilization survey among farmers would also be helpful as they may have various kinds of practices, such as the use of chemical fertilizers, local organic fertilizers (ovine, caprine, mixed manure) or organic fertilizers from other parts of the country (ovine, caprine, bovine, mixed manure).

The vegetation of palm plantations formerly consisted of native species from local camel rangelands, such as *Agathophora alopecuroides* and *Stipagrostis plumosa* (Ozenda, 2004). Although the plantations were set in 1972, their establishment consisted of a single hydro-agricultural development that disturbed the soil locally (Zaid, 2002): the disturbance was limited to a few square meters around each planted tree which were spaced 11m apart. While palm tree plantations used to be well-drained, there is now a lack of maintenance of drainage systems, which combined with the water table rise, makes soils wetter. Also, the water from the water table is increasingly salty, and salt gradually accumulates in the soil over time (Bouarfa *et al.*, 2009). Therefore, with time, weed flora characterizing humid and salty soils and consisting of such species as *Cressa cretica*, *Cyperus rotundus* and *Phragmites australis*, has colonized the area.

Conclusions

The weed flora after 20 years was very different among the three studied crop types, mainly because their management sequences are different (Salama *et al.*, 2016). Weed monitoring over 20 years shows that weed composition is changing over time, particularly in cereal plots and in palm plantations. Whereas changes are likely driven by lack of drainage maintenance and salt accumulation in the case of palm plantations, more studies are needed to understand weed species composition in the cereal plots and greenhouses. This first study on crop weed composition in the Algerian Sahara is only a first step on the path to improved management, and an analysis of weed provenance (e.g., crop seed types and use of organic fertilization) and weed traits should be completed next.

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Table 1. Year of surveys of the 100 palm plantations, 9 cereal plots and 50 greenhouses between 1990 and 2003. One presence-absence plant list was available per year, compiled from three annual surveys: to match the seasonal planting and harvest schedule, surveys were carried out starting in October of each year (x), and repeated in February and June of the following year (x + 1), to give a total of three surveys per year. The data from each set of three surveys were then taken together to fully characterize each October x to June x+1 crop year (ITCMI and ITDAS, 2002).

	Cereal plots	Greenhouses	Palm plantations
1990-91	×	×	×
1991-92		×	
1992-93		×	×
1993-94	×	×	×
1994-95	×	×	
1995-96		×	
1996-97		×	
1997-98		×	×
1998-99	×	×	×
1999-00	×	×	×
2000-01	×	×	×
2001-02	×	×	×
2002-03	×	×	×

Table 2. Results of the Mixed-effects Generalized Linear Models analysing differences in numbers of weed species (species richness lines) or percentages of weed species (other lines) / transect along time. Each crop type was analyzed separately. Two models were compared for analysis: one with time included as an explanatory variable and one without. For these analyses, only the data from 2003 to 2010 were used. If the model with time had a lower AIC (Akaike Information Criterion), time was considered as having a significant effect (i.e. $\Delta AIC > 2$; Burnham & Anderson, 2004). The F and p-value correspond to the model with time included as an explanatory variable.

Variables	AIC model with time	AIC model without time	df	F	p-value
Species richness in cereal plots	405.2	524.1	6	22.01	<0.001
Species richness in greenhouses	750.1	768.8	6	5.21	<0.001
Species richness in palm plantations	463.2	459.9	6	1.42	0.224
Therophytes in cereal plots	412.48	411.05	6	1.75	0.127
Therophytes in greenhouses	867.99	883.54	6	4.58	<0.001
Therophytes in palm plantations	461.4	460.83	6	1.93	0.092
Hemicryptophytes in palm plantations	395.51	392.58	6	1.47	0.206
Complex chorotype in cereal plots	396.86	404.21	6	3.24	0.008
Mediterranean in cereal plots	372.1	393.2	6	5.63	<0.001
Complex chorotype in greenhouses	850.4	865.1	6	4.45	<0.001
Alien in greenhouses	871.3	970.2	6	16.59	<0.001
Complex chorotype in palm plantations	403.9	394.7	6	0.47	0.828
Saharo-Arabian chorotype in palm plantations	424.5	438	6	4.13	0.002

Figure legends are the same for the coloured online version and for the B&W version of the figures.

Fig. 1. Location of the study site in the region of Hassi Benabdellah, northeastern part of Saharan Algeria, about 800 km from Algiers (32°01'N; 5°28'E).

Fig. 2. Correspondence Analysis run on all data (282 samples $\times$ 162 species). Only the most correlated species are shown. Samples are grouped according to the crop types.

Fig. 3. Mean percentage of species / transect in each chorotype, considering crop types separately. For this analysis, only the data from 2003 to 2010 were used: cereal plots (sample unit =200m²), palm tree plantations (sample unit = 1000m²) and greenhouses (sample unit = 50m²). Values are shown as means $\pm$ SE. Bars with common letters do not differ significantly according to Tukey's pairwise comparison tests (p-value > 0.05).

Fig. 4. Mean percentage of species / transect in each life form, considering crop types separately. For this analysis, only the data from 2003 to 2010 were used: cereal plots (sample unit =200m²), palm tree plantations (sample unit = 1000m²) and greenhouses (sample unit = 50m²). Values are shown as means $\pm$ SE. Bars with common letters do not differ significantly according to Tukey's pairwise comparison tests (p-value > 0.05).

Fig. 5. Mean number of weed species in each year from 1990 to 2010 considering crop types separately: in the cereal plots (dot; sample unit =200m²), in the greenhouses (triangle; sample unit = 50m²) and in the palm plantations (cross; sample unit = 1000m²). Analyses could only be run on the data from 2003 to 2010. See results of analyses in Table 2. Values are shown as means $\pm$ SE. Points with common letters do not differ significantly according to Tukey's pairwise comparison tests (p-value > 0.05).

Fig. 6. Percentage of species in a particular chorotype in each year from 1990 to 2010, considering crop types separately: in the cereal plots (sample unit =200m²), in the greenhouses (sample unit = 50m²) and in the palm plantations (sample unit = 1000m²). Analyses were run on the data from 2003 to 2010, on the two most common chorotypes for each crop type. See results of analyses in Table 2. Values are shown as means $\pm$ SE. Points with common letters do not differ significantly according to Tukey's pairwise comparison tests (p-value > 0.05).

Fig. 7. Correspondence Analysis run on cereal plot data (71 samples $\times$ 104 species). Only the most correlated species are shown. Samples are grouped according to the year of study from 2003 to 2010. From 1990 to 2003, there is only one point (in grey) / year.

Fig. 8. Correspondence Analysis run on greenhouse data (139 samples $\times$ 31 species). Only the most correlated species are shown. Samples are grouped according to the year of study from 2003 to 2010. From 1990 to 2003, there is only one point (in grey) / year.

Fig. 9. Correspondence Analysis run on palm tree plantation data (72 samples $\times$ 119 species). Only the most correlated species are shown. Samples are grouped according to the year of study from 2003 to 2010. From 1990 to 2003, there is only one point (in grey) / year.