

Climate change and the potential spread of *Sorghum halepense* in the central area of Argentina based on growth, biomass allocation and eco-physiological traits

Eduardo Sixto Leguizamón · Horacio A. Acciaresi

Received: 15 November 2013 / Accepted: 12 December 2013 / Published online: 19 June 2014
© The Author(s) 2014

Abstract Despite the research dedicated to understand the potential climate change impacts on cropping systems, little attention has been given to potential effects on the geographic range of agricultural weeds. This paper reviews some biological and eco-physiological features of *Sorghum halepense* populations and their current and potential spread in a central eco-region of Argentina. Above ground biomass accumulation of the weed shows very high accumulation rates, which in the case of rhizomes is boosted as the available resources in propagule increases. An increase in temperature by 15 % may increase the relative growth rate (RGR) by 50 % in a 20–90 days growth period. Not only biomass output but also biomass allocation is directly related to adaptation in changing environments. Populations adapted to limited water conditions are able to maintain a higher RGR under water restriction as compared to those adapted to more humid conditions. Regarding the temperature, climate models are

coincident: a range of increase from 0.9 °C in the south to 1.4 °C in the north of Argentina is predicted for 2020–2040, as compared to the period 1961–1990. Concerning the rainfall, not yet a prediction but a real fact is the displacement of isohyets from east to south. The average frequency of the weed in the pool of fields recently surveyed in the central region was 37 %, which increased to 42 % in the field borders. We consider that this frequency is high, since all crop fields are managed with high technology level and herbicides have been applied not only during the crop cycles, but also in previous fallows. The high RGR and other physiological features of weed populations at low water availability, which is more frequent in the west of the surveyed region where the frontier of extensive crops have recently displaced, may explain higher frequencies found. Well-adapted *S. halepense* populations invading rainfed crops in this eco-region will likely to take advantage under the forthcoming forecasted climatic conditions. Since temperatures increase from east to west as shown in climograms, *S. halepense* populations will likely perform even better under the new climate conditions. Coupling the actual management to physiological traits, it is envisaged an increase of the weed frequency in the surveyed eco-regions.

E. S. Leguizamón (✉)
Departamento de Sistemas de Producción Vegetal,
Facultad de Ciencias Agrarias, Universidad Nacional de
Rosario, Santa Fe, Argentina
e-mail: esleguizamón1946@gmail.com

H. A. Acciaresi
Departamento de Tecnología Agraria y Forestal, Facultad
de Ciencias Agrarias y Forestales, Comisión
Investigaciones Científicas (CIC), Universidad Nacional
de La Plata, La Plata, Buenos Aires, Argentina
e-mail: acciaresi@agro.unlp.edu.ar

Keywords Johnson grass · Global warming · Above ground biomass · Relative growth rate · Weed potential spread · Physiological traits · Seeds · Rhizomes

1 Introduction

The global climate is changing and temperature and CO₂ level are considered the major drivers of climate change, with increasing attention being given to its impact on agricultural production systems and weeds (Mc Donald et al. 2009). For crop-weed competition, many experiments characterize the effects of elevated ambient CO₂ on comparative physiology and growth (Ziska 2003). Variation in any factor such as CO₂, temperature, water, or nutrient availability which affects plant growth can also affect weed/crop interactions. Of particular importance are factors that differentially affect weeds and crops (Patterson 1995). Despite the research dedicated to understand the impacts of potential climate change in cropping systems, little attention has been given to the potential effects on the geographic range of agricultural weeds (Mc Donald et al. 2009). Some progress has been made in the understanding of pest (weeds, insects, pathogens) response to climate change, in several cases consistent with climate trends. According to Mc Donald et al. (2009), *Sorghum halepense*, a predominantly Southern U.S. weed species at present, may become common and affect maize production with its damage niche advancing 200–600 km north of its present-day distribution. The same type of warning was done for *S. halepense* in Austria by comparing systematic records since 1990 (Follak and Essl 2012).

Sorghum halepense (L. Pers.), a worldwide weed that can cause severe yield reductions in summer crops and invades extensive areas of the world, is a perennial C4 grass native to Eurasia that reproduces via rhizomes and seeds and is also known as Johnson grass (Warwick and Black 1983). It was introduced as a forage crop in the southern United States of America in the 1800s and in the early 1900s with the same purpose in Argentina. In general, this weed is best adapted to warm and humid conditions of subtropics and new ecotypes have emerged with an array of differences between populations, such as increased seed weight, seedling growth, flowering and resource allocation to rhizomes enabling weed expansion in new areas (Warwick et al. 1984). Although highly selfing, the genetic variation needed for the shifts in the ecology of Johnson grass populations may be provided by the existence of cross pollination and also by the introgression from domesticated sorghum (*Sorghum bicolor* L. Moench.) (Warwick et al.

1984), illustrating yet another mechanism by which weed species gain selective advantages in association with agriculture. Under favorable Argentinian climatic conditions in the spring, rhizomes surviving the winter from previous season provide buds for renewed growth: secondary extensions from the original rhizomes reach the surface generating a crown and new tillers. The tillers produce new rhizomes during the summer, which in turn provide new buds for weed re-growth in the following spring (Oyer et al. 1959; Keeley and Tullen 1979). Each tiller produces an open-lax panicle and up to 350 seeds may be formed in a panicle, depending on the ecotype (Horowitz 1973; Ghersa et al. 1985). There has been extensive research on anatomy, biology, physiology and chemical control of *S. halepense*, as reviewed by McWhorter (1989). Information at population level allows robust models to be built, a valuable tool to understand how and why the weed persists and so to design improved management practices (Cousens and Mortimer 1995). It is at the population level that this weed is being studied since 1979 under the agroecosystems of Argentina (Leguizamón 1983, 1999, 2003; Leguizamón et al. 1986).

The rapid response of weeds to environmental changes may represent a competitive advantage over less aggressive species, including other weeds and crops. The impacts of climate change on single species and ecosystems are likely to be complex, as weeds have rapid dispersal and establishment, invading new areas and increase their environmental range. This ability to occupy new areas can be attributed to evolutionary adaptation of some weed populations occurring in areas experiencing warmer and/or more humid climates.

This paper reviews some biological and eco-physiological features of populations of *Sorghum halepense*, considering its potential spread in a central eco-region of Argentina. We summarized the pattern of dry matter accumulation of the weed comparing three plant densities originated in rhizomes, and the influence of a crop (soybean) and soil management. While we describe differences in the accumulation pattern due to the “initial capital” of seeds and rhizomes we use data to parameterize an expo-lineal competition model for predicting the effects of changes in temperature and light. We also show the relative growth rate (RGR) and leaf gas exchange in populations that are presumable adapted to different

climate conditions. The weed frequency in field crops and margins growing in a central area of the country is also presented. Finally, prospects for its spread in the forthcoming decades within the global warming scenario are presented in the selected eco-region, where we also comment the potential use of remote sensing techniques to predict the risk of invasion in new areas.

2 Pattern of above-ground dry matter accumulation

In field experiments, three initial rhizome densities of the weed (3, 30 and 300 g m⁻², thereafter named as low, medium and high, respectively) were settled in randomized four replicates blocks, which included the weed in monoculture and also with soybean plants (maturity group, MG VI) sown at 0.7 m between rows. Considering the thermal time (growing degree days, GDD) accumulated above 15 °C, several harvests were made along the period 0–1,400 GDD (Fig. 1). The above-ground pattern of weed dry weight dynamics was modeled using a third order polynomial, as follows (Leguizamón 2003; Leguizamón, unpublished):

$$y = a + b \cdot \Theta T + c \cdot \Theta T^2 + d \cdot \Theta T^3 \quad (1)$$

where y represents the accumulated above-ground biomass (g m⁻²) at any thermal time (ΘT), a , b , c and d are parameters.

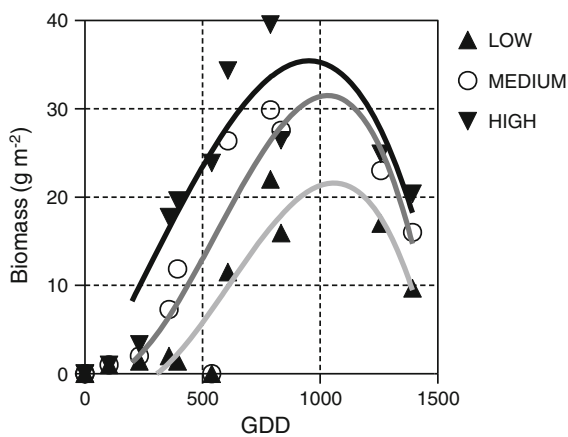


Fig. 1 *Sorghum halepense* above-ground (shoots + tillers) biomass accumulation pattern at three initial population densities in monoculture. Models statistically differ at $p < 0.05$

In each weed density, models depict three distinctive periods: before 180–220 GDD above ground biomass (shoot and tillers) is very low, time in which the weed is more sensitive to herbicides (Satorre et al. 1985; Vitta and Leguizamón 1991). From 180 to 900–1100 GDD, biomass accumulation increases up to its maximum (1200, 960 and 460 g m⁻² in high, medium and low densities, respectively) in parallel to RGR decrease from 0.266 to 0.055 g g⁻¹ day⁻¹. From 900–1100 to 1400 GDD, RGR is negative, denoting the exportation of photosynthates to subterranean structures that ensure sustainability: the rhizomes. Generation of new rhizomes (tertiary) starts by 180–220 GDD. At any weed density, the maximum above-ground weed biomass was significantly decreased (30 %) by the crop (not shown). Differences in above-ground growth rate due to initial propagule type and characteristics have been studied by Lolas and Coble (1980a, b) and Leguizamón (1997, 1999). The RGR during the 0–900 GDD period increases from 0.085 to 0.548 g g⁻¹ day⁻¹ as rhizome length increases from one to nine nodes (or 3–25 mm length, Table 1). As seen, above-ground biomass accumulation of the weed is very high, which in the case of rhizomes, is boosted as the available resources in propagule increases. Also, soybean competition may substantially reduce weed biomass, which may be enhanced if the time to reach crop critical leaf area is shortened (e.g.: improving spatial arrangement by reducing distances between rows and/or selecting proper cultivars according to sowing date).

Table 1 RGR of *Sorghum halepense* above-ground biomass of plants originated in different propagules

Origin of the plant	Source	RGR
Seed	Leguizamón 2003 (Exp. 1)	0.049
Seed	Leguizamón 2003 (Exp. 2)	0.048
Seed	Oyer et al. 1959	0.051
Seed	Leguizamón 2003 (Exp. 3a)	0.072
Uninodal rhizome	Leguizamón 2003 (Exp. 3a)	0.085
Short rhizome 40 mm	Leguizamón 2003 (Exp. 3b)	0.182
Rhizome 25 mm	Lolas and Coble 1980a, b	0.250
Long rhizome 100 mm	Leguizamón 2003 (Exp. 3b)	0.258
Rhizome 100 mm	Lolas and Coble 1980a, b	0.298
Rhizome 200 mm	Lolas and Coble 1980a, b	0.325
Rhizome 250 mm	Lolas and Coble 1980a, b	0.548

3 Temperature and irradiance: assessing variations on above-ground dry matter accumulation in a simulation model

In several pot experiments, the above-ground biomass accumulation pattern of plants originated from seeds and rhizomes were determined in several harvests after weed emergence and the data were used to parameterize the expo-linear model by Scaife and Morris (1987) and Benjamin and Park (2007). These authors claim that the combined effects of temperature and irradiance may be assumed as the sum of its reciprocals, using an approach based on resistances of an electric circuit. Thus, within certain limits, plant growth (above-ground biomass accumulation) is proportional to the reciprocal of temperature and irradiance. The model was validated with independent data and then used to simulate the effects on biomass accumulation according to changes in temperature and irradiance, which is influenced by plant density (Leguizamón 2008):

$$r = (1/w) \cdot (dw/dt) = 1 / (1/(a \cdot (T - T_b)) + (b \cdot I)) \quad (2)$$

where r is the RGR ($\text{g g}^{-1} \text{day}^{-1}$), w is the initial weight (g pl^{-1}), a is the conversion coefficient, T is the actual daily temperature, T_b is the base temperature, b is the conductance of r as related to irradiance ($\text{g g}^{-1} \text{m}^{-2} \text{MJ}^{-1}$), and I is the irradiance (MJ m^{-2}).

The Eq. 2 may be improved by incorporating factors affecting the proportion of intercepted irradiance as the leaf area index (LAI), the light extinction coefficient and plant density, as well as the radiation use efficiency (RUE):

$$r = 1 / (1/(a(T - T_b)) + (b \cdot \Phi \cdot I)) \quad (3)$$

$$\Phi = (1 - \exp(-n \cdot K \cdot SL)) / n \cdot K \cdot SL \quad (4)$$

where Φ is the efficiency of leaf area for irradiance interception, n is plant density (plants m^{-2}), K is the light extinction coefficient, and SL is the leaf area per plant (m^2).

The light extinction coefficient accounts for differences in leaf angle and also its distribution within the canopy; thus its inclusion in Eq. 4 makes the self-shading function a proportion of irradiance interception per unit 'effective' leaf area. The leaf area (SL) was calculated with an allometric relationship as follows:

$$SL = F \cdot w^\theta \quad (5)$$

where F is an allometric constant, θ is the relationship among both variables (SL and K), and w is the plant weight (g pl^{-1}).

By 50 days after emergence, RGR of shoots originated in seeds is significantly higher than that of shoots originated in rhizome (Fig. 2a). The estimates shown in this figure are within the range presented in Table 1 and also in accordance to those reported by Hunt et al. (2002). Figure 2b shows that above-ground accumulated biomass increased as original rhizome length increased.

Predicted outputs of above-ground biomass, radiation use efficiency (RUE) and RGR as affected by changes in temperature, irradiance and weed density are shown in Fig. 3. This figure shows simulated changes in plant biomass when the base temperature increases by 15 % (Fig. 3a), irradiance decreases by 25 % (Fig. 3b) and weed density increases ten times (Fig. 3c), which in turn affects RUE because of shading (Fig. 3d). An increase in temperature by 15 % may increase the RGR by 50 % in the 20–90 days growth period (Fig. 3e). Finally, we may point out that not only biomass output but also biomass allocation is directly related to adaptation to changing environments (Lambers et al. 1998).

4 Relative growth rate and leaf gas exchange of populations of different geographical origins under two levels of soil water availability

In this section we explore if the variation in soil water availability during the growth period modifies crucial

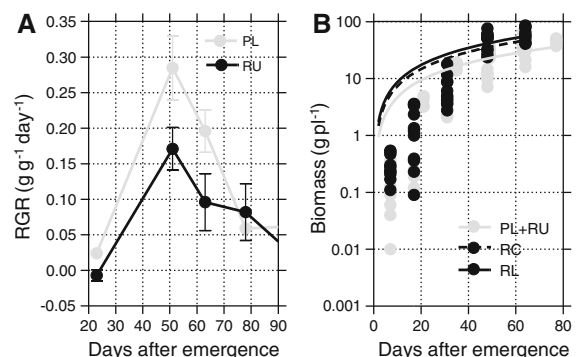


Fig. 2 a RGR of above-ground biomass (shoots + tillers) originated in seeds (PL) and uninodal rhizome (RU), and b above-ground biomass accumulation in plants originated in seeds and uninodal (PL + RU), short (RC-4 nodes) and long (RL-10 nodes) rhizomes

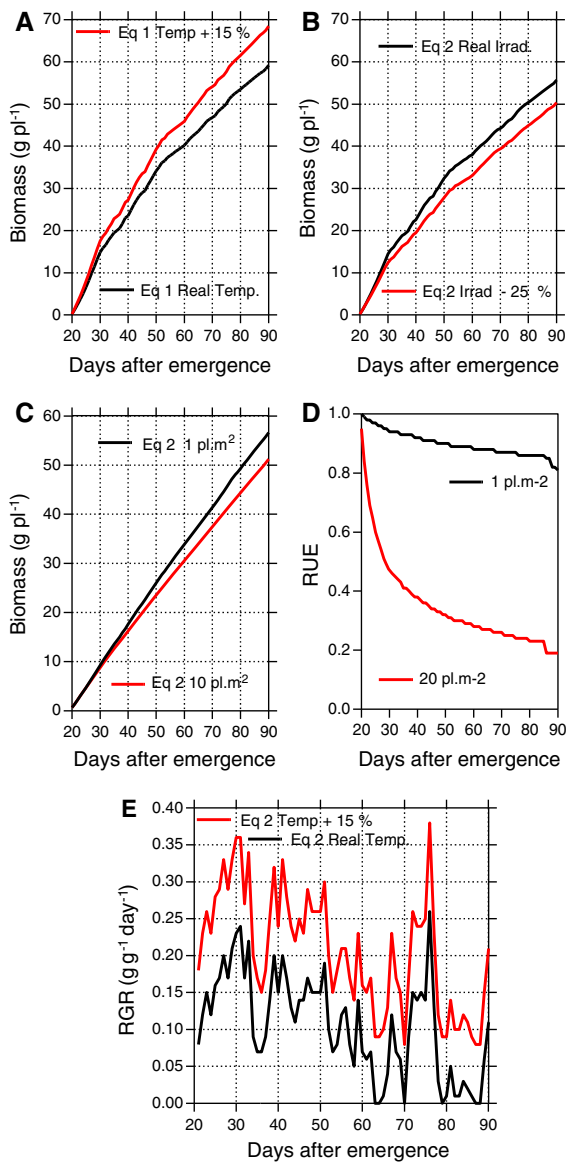


Fig. 3 **a** Simulated changes in the above ground biomass when base temperature increased by 15 % (Eq. 2); **b** by 25 % (Eq. 3); **c** changes in weed density ($\times 10$) (Eq. 4); **d** simulated effect of two weed densities on RUE (Eq. 4); and simulated effects of changes in temperature on daily RGR (Eq. 2)

physiological processes in *S. halepense* populations growing and presumably adapted to different climates. Rhizomes were collected in three areas located in the boundaries of an imaginary circle in the center of a surveyed ample area (see Fig. 13): climograms of Río IV, Santa Rosa and Rojas are shown in Figs. 4, 5 and 6. Rhizomes were planted in large pots and after appropriate establishment, plants were then submitted to

differential water availability in controlled conditions (Acciaresi et al. 2012). For the purpose of this paper, we only compare three populations under field capacity (FC) and drought (DR). The multivariate analysis demonstrated a significant effect of population origin and water level along the period studied (21–46 days after weed emergence) on RGR and leaf gas exchange.

Under FC conditions, the population collected in a more humid location (Rojas) exhibited higher RGR as compared to that of populations collected in sub-humid locations of Sta Rosa and Río IV (Fig. 7a). Under DR conditions, RGR decreased along the period of study in all populations, but it was significant lower in the population from the humid location (Rojas) 30 days after emergence (Fig. 7b).

Plants of different origins maintained a steady-constant leaf CO_2 assimilation (A) under FC conditions (Fig. 8a), which was significantly higher in the population collected in the humid region (Rojas). Under DR conditions, A showed a significant decrease 30 days after emergence (Fig. 8b).

As observed for RGR and A, the stomatal conductance (g_s) and transpiration (E) were higher in the population of humid region along the whole period of study when grown in FC conditions (Figs. 9a, 10a), but significant decreases were noticed 30 days after emergence under DR conditions (Figs. 9b, 10b).

It has been experimentally demonstrated that populations adapted to limited water conditions (Río IV and Sta Rosa) are able to maintain higher RGR as compared to that adapted to more humid conditions (Rojas) under water restriction. Soil available water provided by rainfall is crucial in the rainfed production systems where extensive crops are cultivated in Argentina, a feature that is magnified as the cultivated area expands to the west. Climograms shown in Figs. 4, 5 and 6, illustrate differences in climate conditions (e.g. rainfall) that may be encountered in each location.

In many plants species, the fluctuation of soil water availability along the crop cycle affects not only growth, but also biomass allocation and crop productivity. Different traits have been related to the tolerance to water deficit, such as an increased density of root system, the maintenance of root elongation with decreased soil water availability (Acciaresi and Guiamet 2010), the ability to maintain stomata opened under low leaf water potential (Geddes et al. 1979; Stuart et al. 1985; 1987; Patterson 1995; Leguizamón et al. 2011; Acciaresi et al. 2012), osmotic adjustment

Fig. 4 Climogram of Río IV (33°08'S 64°21'W). <http://es.climate-data.org/location/1905/> Driest month is July, 14 mm rainfall. December is the most humid month: 132 mm. Accumulated annual rainfall is 809 mm. Hottest month is January (23.6 °C). Coldest month is June (9.9 °C). Axes Y1: temperature in °F and °C, Y2: rainfall (mm). X: months of the year

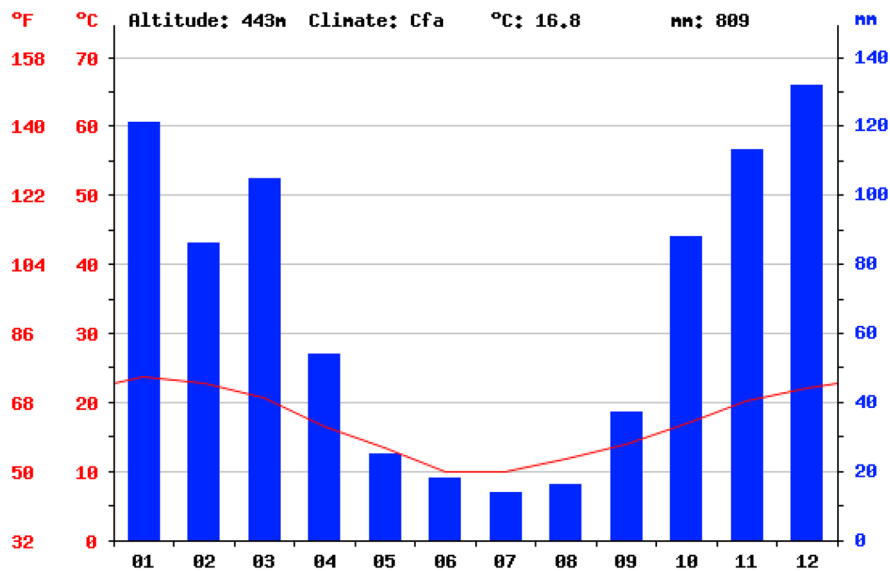
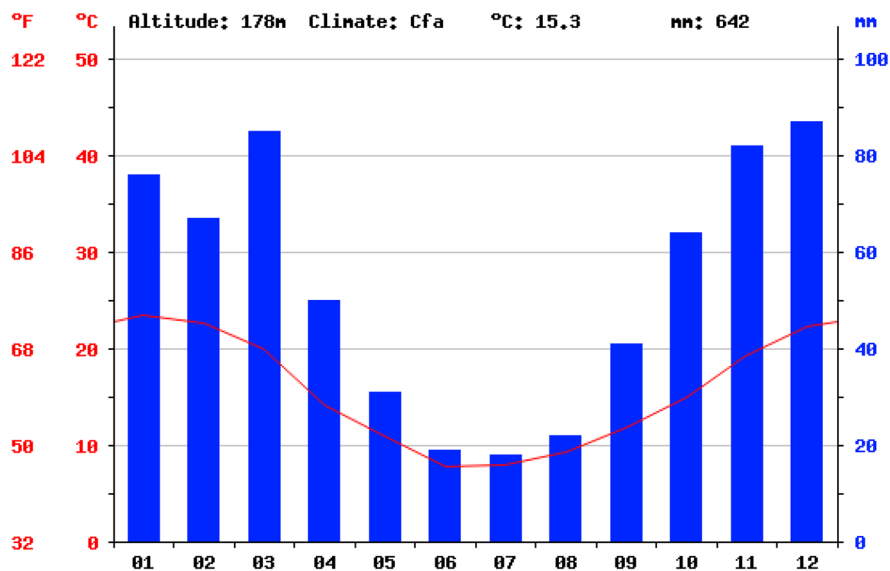


Fig. 5 Climogram of Santa Rosa (36°37'S 64°17'W). <http://es.climate-data.org/location/1919/> Driest month is July, 18 mm rainfall. December is the most humid month: 87 mm. Accumulated annual rainfall is 642 mm. Hottest month is January (23.4 °C). Coldest month is June (7.7 °C). Axes Y1: temperature in °F and °C, Y2: rainfall (mm). X: months of the year



(Stuart et al. 1985; Hsiao and Xu 2000) and also the ability to decrease RGR and reproduction (Ray et al. 1997; Ray and Sinclair 1997). It has also been reported that under a situation of water competition, several weeds make wasteful water consumption (“luxury consumption”, Patterson 1995), a response related to the physiological behavior of the stomata, being less sensitive to low leaf water potential as compared to that of the crops (Scott and Geddes 1979; Geddes et al. 1979; Patterson and Flint 1983; Patterson 1995). Stuart et al. (1985) determined that *S. halepense* grown

in monoculture was able to maintain high photosynthesis rates (ca. $40 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and stomatal conductance ($0.48 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$) even when leaf water potential was -1.6 MPa . When the weed grew in competition with different corn genotypes, stomatal conductance was maintained at $0.099 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ and photosynthetic rate at $17.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ even under leaf water potential of -2.6 MPa . This indicates that *S. halepense* is highly capable of an active gas exchange and also to maintain photosynthesis even under water deficit.

Fig. 6 Climogram of Rojas (34°12'S 60°44'W). <http://es.climate-data.org/location/1907/>. Driest month is July, 39 mm rainfall. March is the most humid month: 128 mm. Accumulated annual rainfall is 956 mm. Hottest month is January (23.3 °C). Coldest month is July (9.8°C). Axes Y1: temperature in °F and °C, Y2: rainfall (mm). X: months of the year

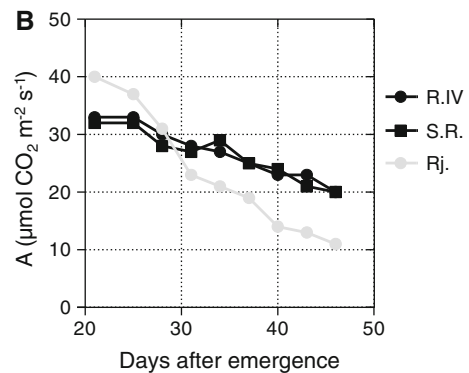
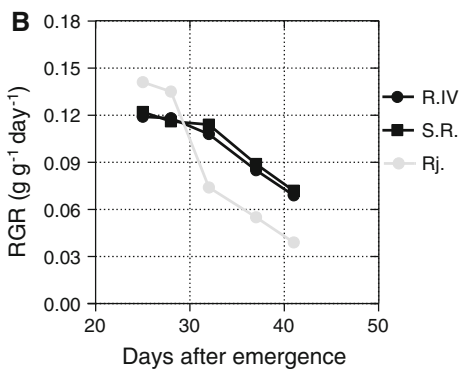
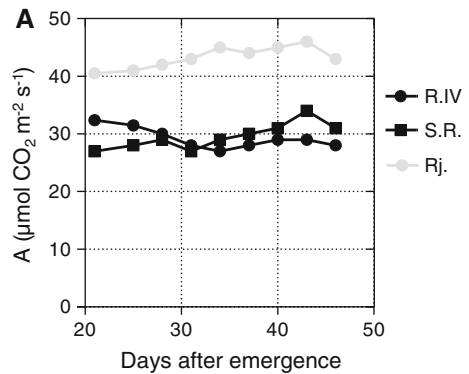
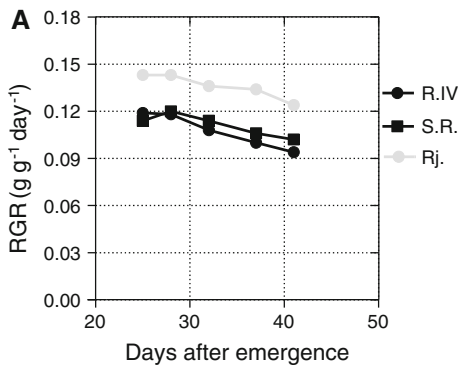
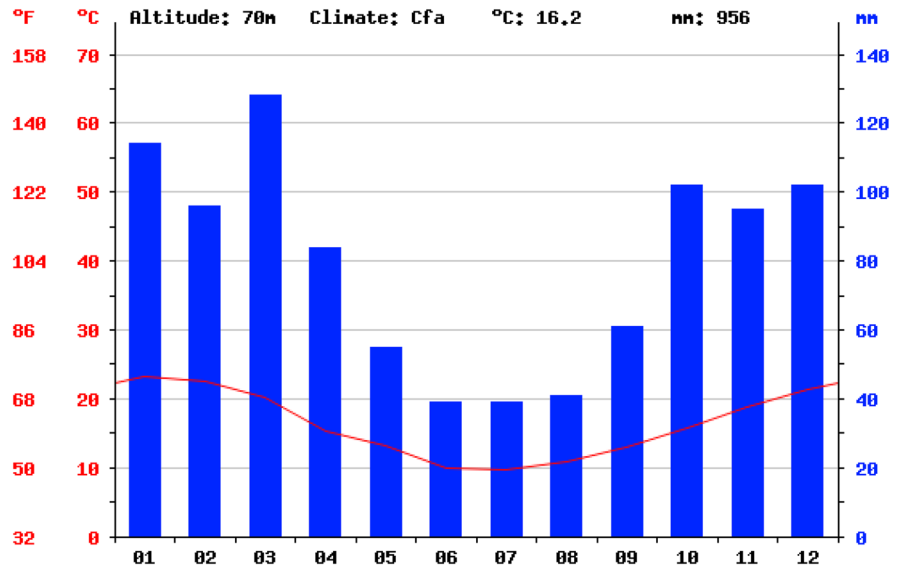


Fig. 7 RGR of *S. halepense* populations: Río IV (R.IV), Santa Rosa (SR) and Rojas (Rj), 21 days after emergence under **a** FC and **b** DR. Redrawn from Acciaresi (2008)

Fig. 8 Photosynthetic rate of *S. halepense* populations: Río IV (R.IV), Santa Rosa (SR) and Rojas (Rj) 21 days after emergence under **a** FC and **b** DR. Redrawn from Acciaresi (2008)

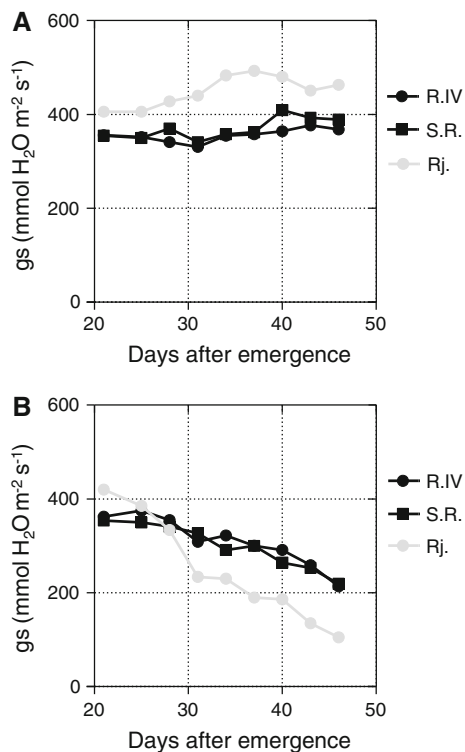


Fig. 9 Stomatal conductance of *S. halepense* populations: Río IV (R.IV), Santa Rosa (SR) and Rojas (Rj) 21 days after emergence under **a** FC and **b** DR. Redrawn from Acciaresi (2008)

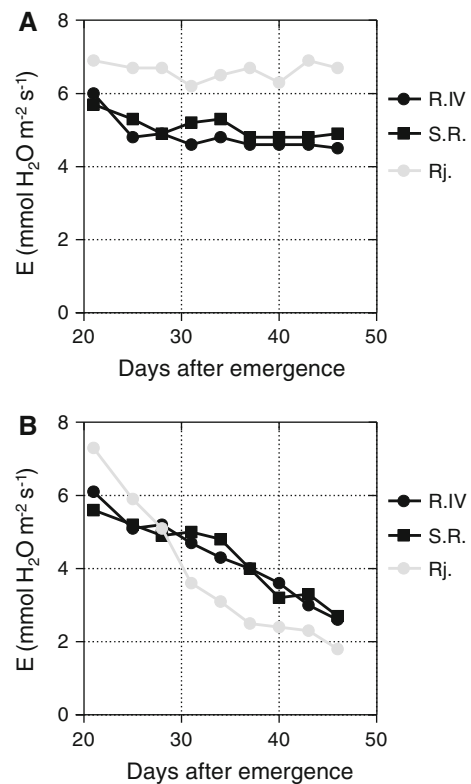


Fig. 10 Transpiration rate of *S. halepense* populations: Río IV (R.IV), Santa Rosa (SR) and Rojas (Rj) 21 days after emergence under **a** FC and **b** DR. Redrawn from Acciaresi (2008)

5 Argentina climate: present situation and prospects for the agriculture in the global change summit

Regarding temperature, climate models are coincident: an increase from 0.9 °C in the south and 1.4 °C in the north of Argentina is predicted for 2020–2040, as compared to the period 1961–1990 (Fig. 11a). Although prospects for rainfall are variable, they are consistent on predicting that minor changes will occur (Fig. 11b) and extreme events (high frequency rainfalls) are likely to increase. Following the analysis of the vulnerability of the agricultural production and the scenario with increased temperatures and similar rainfalls, yields of wheat and corn may be penalized in the north of the country, but they may be boosted in the south. On the other hand, soybean yields may be benefited in both areas (Convención Marco de las Naciones Unidas sobre el cambio climático 2007).

Concerning the rainfall, not yet a prediction but a real fact is the displacement of isohyets from east to south, thus increasing the water availability, a crucial factor defining the potential yield of crops (and also weeds), in the central plains of Argentina where extensive rainfed crops are cultivated (Fig. 12).

6 A survey on the frequency of weed

During 2011–2012 a weed survey was performed in several Eco-regions of central Argentina requested and supported by the National Service of Food Security (SENASA). Inventories also included field borders. Extra points were added along borders in significant roadways. Census included ten samples of 10 m² in each one of selected fields cultivated with extensive crops (wheat, soybean, sunflower, corn and lucerne) (Leguizamón et al. 2011). For the purpose of this paper, pooled frequency of all *S. halepense* data

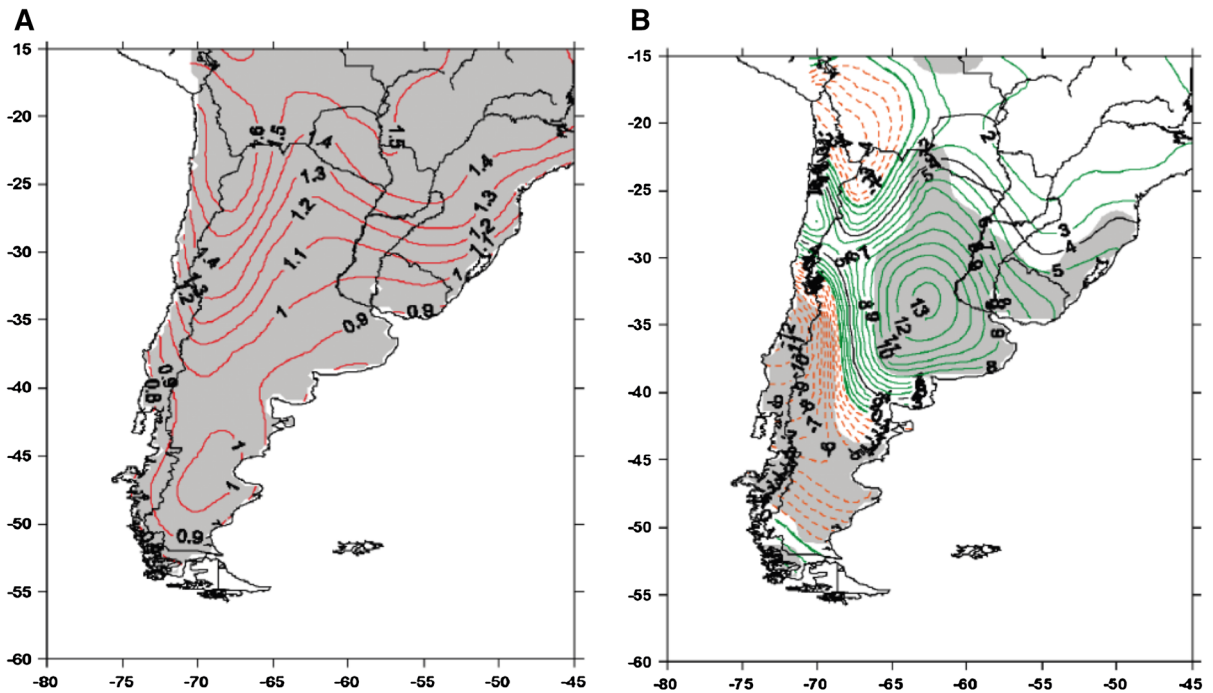
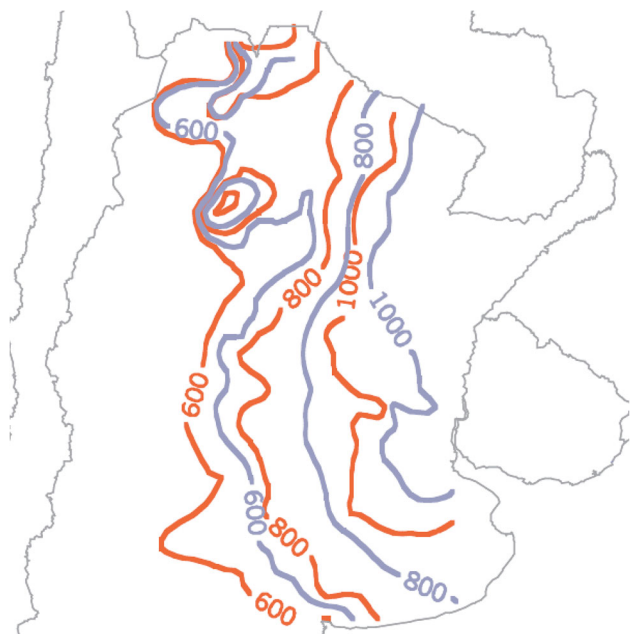


Fig. 11 Predicted annual mean **a** air temperature (°C) mean **b** rainfall (mm) changes in period 2020–2040 as compared to 1961–1990

Fig. 12 West displacement of isohyets. *Light grey* (1950–1969), *dark grey* (1980–1999) isohyets



were interpolated and mapped by using GIS software (Surfer, Golden Software Inc. 2000). The grid was created by using the inverse median distance as the interpolation method (Fig. 13). In the center, an

imaginary circle has been drawn by using the three locations where populations of the weeds were collected to test physiological traits (previous section) as boundaries. It may be seen that interpolated

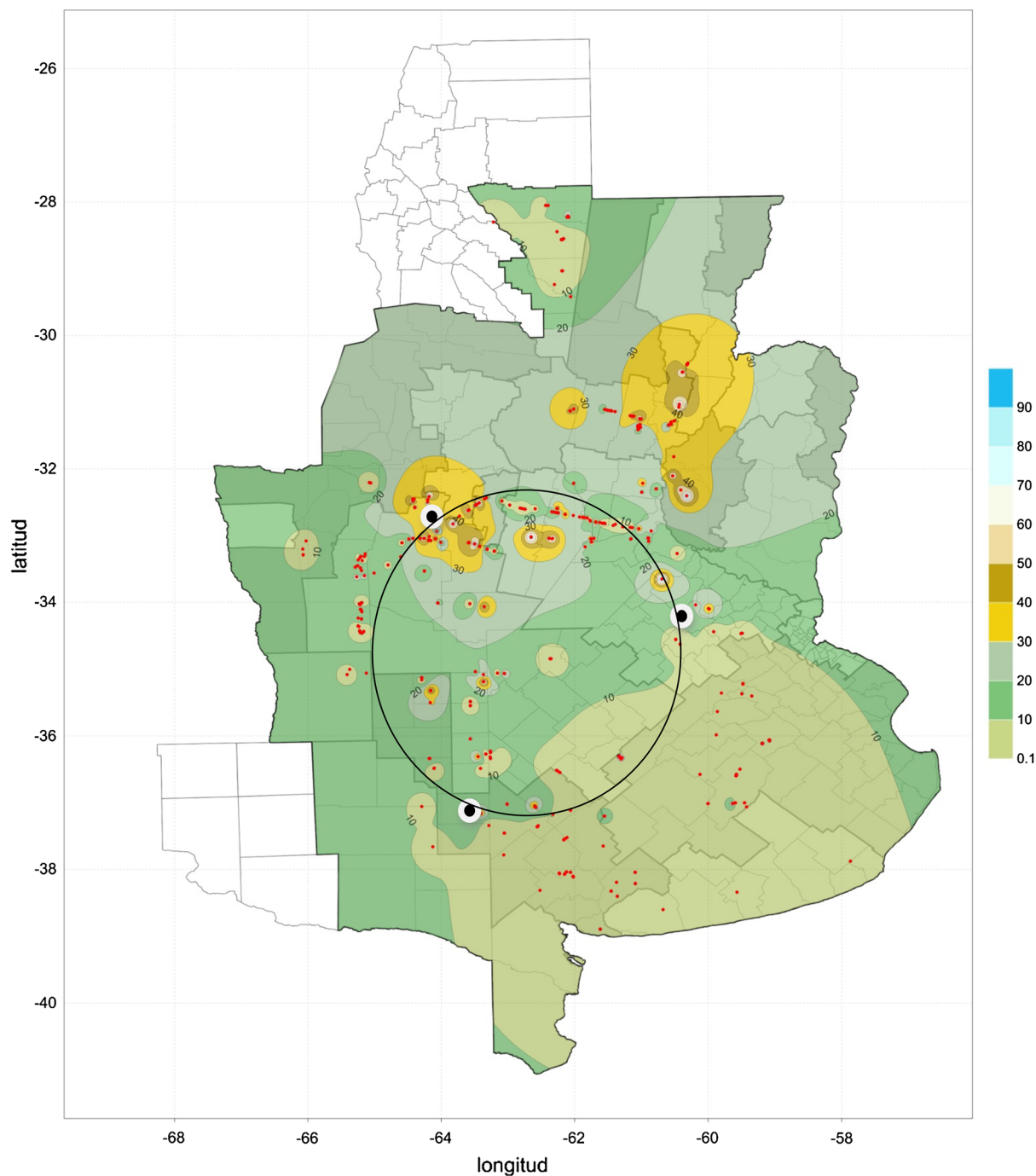


Fig. 13 Frequency of *S. halepense* in central region of Argentina (data from a survey made in December 2010–February 2011). Tiny points indicate sampling areas. Note that the frequency boundaries increases from the southeast (10 %) to

frequencies clearly increase from the South-East (frequency boundary = 10) to the Northwest (frequency boundary lines = 20, 30, 40).

the north and northwest (30–40 %). The populations to test physiological traits under two levels of water availability were collected in the boundaries of an imaginary circle drawn in the center of this ample area

The average frequency of the weed in the pool of fields was 37 %, which increased to 42 % in the borders. We consider that this frequency is high, since

all crop fields are managed with high technology level and herbicides have been applied not only during the crops cycles, but also in previous fallows. The high RGR and other physiological features of weed populations at low water availability, which is more frequent in the west of the surveyed region where the frontier of extensive crops have recently displaced, may explain the higher frequencies found in the northwest surveyed area.

6.1 Prospects

Characteristics of Johnson grass that aid in its fast colonization and spread include: (a) high RGR even under water restriction, and rapid formation of dense rhizomes that host meristematic tissue responsible for regenerating new plants (Anderson et al. 1960; Leguizamón 2003), (b) moderate to high drought resistance coupled with luxury water consumption (Anderson et al. 1960; Acciaresi et al. 2012), which give competitive advantages; (c) salt tolerance (Yang et al. 1990); (d) abundant seed production with seeds that remain viable for 2–5 years prior to germination (Leguizamón 1986; Allen 1990); (e) possible production of toxins that are allelopathic (Warwick and Black 1983; Acciaresi and Asenjo 2003); and (f) several post-dispersal mechanisms associated with anthropogenic causes (irrigation water disperse the seeds and harvest machinery and farming equipments re-disperse seeds, Scopel et al. 1988), grazing animals (Ghersa et al. 1993; Hartzler et al. 1991) and also as contaminant in commercial seeds (Allen 1990). Once dispersed, complementary strategies of both propagules (seeds and rhizomes) take advantage of open niches and available resources and colonize very soon the areas.

Many efforts are underway to predict changes in the distribution of invasive plants under climate change (Kriticos et al. 2007; Mc Donald et al. 2009) but relatively few of these accounted for the eco-physiological characteristics of the species populations. Approaches to predictive modeling such as CLIMEX, utilize climate data for an invasive plant to its home range or known range, and map these parameters on to new potential ranges. These models can predict changes in weed distribution under climate change by developing scenarios based on increased temperatures and/or other climatic parameters (Mc Donald et al. 2009). CLIMEX models have provided

numerous useful predictions on the spread of invasive plants, including attempts to predict changes in weed distribution due to warmer temperatures and other climatic alterations predicted by climatic change models (Pattison and Mack 2008).

Well adapted *S. halepense* populations invading rainfed crops in eco-region V will likely to take advantage under the forthcoming climatic change conditions, since prospects forecast increasing temperatures and isohyets show an actual displacement to the west. Since temperatures increase from east to west as it has shown in climograms (Figs. 4, 5, 6). *S. halepense* populations will likely perform even better under the new conditions. Coupling the actual management to physiological traits in the selected scenario, it is envisaged an increase of the weed frequency in the eco-regions surveyed.

A further restriction for the prediction of spread is that the default methodology when undertaking predictive exercises assumes plants as static entities. Changes in weed distributions however, may often reflect evolutionary changes and are likely related to anthropogenic influences such as cropping practices (Clements et al. 2004). For many years, it was thought that weeds would not develop resistance to glyphosate on a comparable scale to the insecticide resistance, concerns that emerged in the 1950s and 1960s (Gressel and Segel 1978). Now, however, glyphosate resistance is worldwide spread (Heap 2013) and this is the case for *S. halepense* in Argentina. A resistant biotype appeared in 2006 (Vila-Aiub et al. 2007) in the northeast of the country, but resistant biotypes are now found in several Eco-regions. In a survey recently made by REM-Aapresid (Rem-Aapresid 2012) more than 200 cases of infested fields were reported only within the limits of the circle of surveyed area. Thus, weeds have a strong potential to evolve in the presence of such an intense and widely imposed selection pressure. Similarly, Baker's (1965) suggested that weed success was primarily due to possession of a "general-purpose genotype", and it denotes a strategy that weeds utilize extensively in having genotypes that allow a wide degree of phenotypic plasticity and an adequate and sustained level of heterozygosity. There are many examples of weed success due largely to genetic change (Clements et al. 2004) and the mechanisms of such alterations are often subtle because large proportion of weeds is predominantly selfing. Some of these mechanisms include occasional

outcrossing within selfing populations, storage of genetic variations in seed banks, and evolution of phenotypic plasticity. Thus, the consideration of weed evolution should lead to improved predictive power of the models (Clements and Di Tommaso 2011, 2012).

A further approach that could improve quarantine/prevention actions and models is the remote sensing. Remotely sensed images have a number of features, which make them ideal for predicting the area enlargement of invasive species. Remote sensing technologies look in the electromagnetic spectrum, which allows better detection of vegetation at regional scales that would be cost-prohibitive using ground-based visits. The ability to detect invasive plants using remotely sensed data has increased with improved sensors, computer technology, and classification techniques (Lass et al. 2005). Remotely sensed data can also aid in developing spatially explicit predictive habitat models and estimating distributional vectors and pathways. This may provide land managers a means to evaluate current and future weed control needs. For example, a spatial distribution and risk assessment of *S. halepense* has been modeled for the Big Bend National Park (USA) by using remotely sensed and GIS data. Models can represent an early detection tool to prioritize conservation efforts (Young and Schrader 2007).

References

- Acciaresi HA (2008) Respuestas morfológicas y fisiológicas en dos híbridos de *Zea mays* y poblaciones de *Sorghum halepense* inducidas por la competencia frente a la variación de agua edáfica. La Plata, Universidad Nacional de La Plata. Tesis Doctoral, pp 205
- Acciaresi HA, Asenjo CA (2003) Efecto alelopático de *S. halepense* (L.) Pers. sobre el crecimiento de plántula y la biomasa aérea y radical de *Triticum aestivum* (L.). *Ecológia Austral* 13:49–61
- Acciaresi HA, Guiamet JJ (2010) Below- and above-ground growth and biomass allocation in maize and *S. halepense* in response to soil water competition. *Weed Res* 50: 481–492
- Acciaresi H, Yannicari M, Leguizamón E, Guiamet J (2012) Leaf gas exchange and competitive ability of *Zea mays* and *S. halepense* as affected by water competition. *Acta Agron Hung* 60:231–246
- Allen JA (1990) Establishment of bottomland oak plantations on the Yazoo National Wildlife Refuge Complex. *South J Appl For* 14:206–210
- Leguizamón ES, Berbery MT, Cortese P, García Sampedro C, Heit G, Ochoa MC, Sobrero MT, Arregui C, Sánchez D, Scotta R, Lutz A, Amuchástegui, A, Gigón R, Marchessi JE, Núñez C, Zorza E, Rivarola R, Scapini E, Fernández M, Suárez CE, Troiani H (2011) Vigilancia Fitosanitaria en Argentina: detección precoz de malezas cuarentenarias. In: XXXII Reunión Argentina de Botánica. Posadas, Argentina, pp 42
- Anderson LE, Appleby AP, Weseloh JW (1960) Characteristics of Johnson grass rhizomes. *Weeds* 8:402–406
- Baker HG (1965) Characteristics and modes of origin of weeds. In: Baker HG, Stebbins GL (eds) *The genetic of colonizing species*. Academic Press, New York, pp 147–168
- Benjamin LR, Park SE (2007) The conductance model of plant growth and competition in monoculture and species mixtures: a review. *Weed Res* 47:284–298
- Clements DR, Di Tommaso A (2011) Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Res* 51:227–240
- Clements DR, Di Tommaso A (2012) Predicting weed invasion in Canada under climatic change. Evaluating evolutionary potential. *Can J Plant Sci* 92:1013–1020
- Clements DR, Di Tommaso A, Jordan N, Booth B, Murphy SD, Cardina J, Doohan D, Mohler C, Swanton CJ (2004) Adaptability of plants invading North American cropland. *Agric Ecosyst Environ* 104:379–398
- Convención Marco de las Naciones Unidas sobre el Cambio Climático (2007) 2ª Comunicación Nacional de la República Argentina, pp 199
- Cousens R, Mortimer AM (1995) *Dynamics of weed populations*. Cambridge University Press, Cambridge
- Follak S, Essl F (2012) Spread dynamics and agricultural impact of *Sorghum halepense*, an emerging invasive species in central Europe. *Weed Res* 53:53–60
- Geddes RD, Scott HD, Oliver LR (1979) Growth and water use by common cocklebur (*Xanthium pensylvanicum*) and soybean (*Glycine max*) under field conditions. *Weed Sci* 27:206–212
- Ghersa CM, Satorre EH, van Esso ML (1985) Seasonal patterns of Johnsongrass seed production in different agricultural systems. *Isr J Bot* 34:24–31
- Ghersa CM, Martínez-Ghersa MA, Satorre EH, van Esso ML, Chichotky G (1993) Seed dispersal, distribution and recruitment of seedlings of *S. halepense* (L.) Pers. *Weed Res* 33:79–88
- Golden Software Inc. (2000) *Surfer 3.2 User's guide*. Golden Software Inc., Golden, CO
- Gressel J, Segel LA (1978) The paucity of plants evolving genetic resistance to herbicides: possible reasons and implications. *J Theor Biol* 75:349–371
- Hartzler RG, Gover A, Stellingwerf J (1991) Factors affecting winter survival of Johnson grass (*Sorghum halepense*) rhizomes. *Weed Technol* 5:108–110
- Heap I (2013) The international survey of herbicide resistant weeds (online). <http://www.weedscience.org/In.asp>. Accessed 6 Nov 2013
- Horowitz M (1973) Spatial growth of *Sorghum halepense*. *Weed Res* 13:200–208
- Hsiao TC, Xu LK (2000) Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport. *J Exp Bot* 51:1595–1616
- Hunt R, Causton DR, Shipley B, Askew AP (2002) A modern tool for classical growth analysis. *Ann Bot* 90:485–488

- Keeley PE, Tullen RJ (1979) Influence of planting date on the growth of Johnsongrass (*Sorghum halepense*) from seed. *Weed Sci* 27:554–558
- Kriticos DJ, Yonow T, Mc Fadyen RE (2007) The potential distribution of *Chromolaena odorata* (Siam weed) in relation to climate. *Weed Res* 45:246–254
- Lambers H, Chapin III F, Pons T (1998) Growth and allocation. In: Lambers HF, Chapin III F, Pons T (eds) *Plant physiological ecology*. Springer, New York, pp 299–351
- Lass LW, Prather TS, Glenn NF, Weber KT, Mundt JT, Pettigill J (2005) A review of remote sensing of invasive weeds and example of the early detection of spotted knapweed (*Centaurea maculosa*) and babybreath (*Gysophila paniculata*) with a hyperspectral sensor. *Weed Sci* 53:242–251
- Leguizamón ES (1986) Seed survival and patterns of seedling emergence in *S. halepense* (L.) Pers. *Weed Res* 26:397–403
- Leguizamón ES (1983) Dinámica poblacional de sorgo de Alepo (*Sorghum halepense* L. Pers.) en soja. Enfoque del estudio. INTA Informe Técnico No. 32:13
- Leguizamón ES (1997) Refinamiento del modelo poblacional de sorgo de Alepo (*Sorghum halepense* L. Pers.). Efecto de la longitud de los rizomas. Optimización del impacto herbicida. In: VI Congreso Sociedad de la Sociedad Española de Malherbología. Valencia, Spain, pp 96–102
- Leguizamón ES (1999) The refinement of the population model of *S. halepense* (L.) Pers. under a soybean crop. In: Proceedings of the 1999 British crop protection conference-weeds, Brighton, UK, pp 364–372
- Leguizamón ES (2003) Biología Poblacional de sorgo de Alepo: Complementariedad de estrategias y efectos del sistema en la dinámica de la maleza. Rosario, Universidad Nacional de Rosario. Tesis Doctoral, pp 135
- Leguizamón ES (2008) Crecimiento de *Sorghum halepense* L. Pers. Efectos del tipo y tamaño de propágulo. Ajuste de un modelo de conductancia. In: XXXI Congreso de la Sociedad Argentina de Fisiología Vegetal (SAFV). Rosario, Argentina, pp 18
- Leguizamón ES, Brovelli E, Allieri L, Giuggia AE (1986) Dinámica poblacional de sorgo de Alepo (*Sorghum halepense* L. Pers.) en la secuencia trigo/soja. IDIA-INTA 437–440:44–48
- Leguizamón E, Yannicari M, Guiamet J, Acciaresi H (2011) Growth, gas exchange and competitive ability of *S. halepense* populations under different soil water availability. *Can J Plant Sci* 91:1011–1025
- Lolas PC, Coble HD (1980a) Johnsongrass (*Sorghum halepense*) growth characteristics as related to rhizome length. *Weed Res* 20:205–210
- Lolas PC, Coble HD (1980b) Morphology and development of Johnsongrass plants from seeds and rhizomes. *Weeds* 9:58–562
- Mc Donald A, Riha S, Di Tommaso A, De Gaetano A (2009) Climate change and geography of weed damage: analysis of US maize systems suggests the potential for significant range transformation. *Agric Ecosyst Environ* 130:131–140
- McWhorter CG (1989) History, biology and control of Johnsongrass. *Reviews of Weed Science* 4:21–85
- Oyer BE, Gries GA, Rogers BJ (1959) The seasonal development of Johnsongrass plants. *Weeds* 7:13–19
- Patterson DT (1995) Effects of environmental stress on weed/crop interactions. *Weed Sci* 43:483–490
- Patterson DT, Flint EP (1983) Comparative water relations, photosynthesis and growth of Soybean (*Glycine max*) and seven associated weeds. *Weed Sci* 31:318–323
- Pattison RR, Mack RN (2008) Potential distribution of invasive tree *Triadica sebifera* (Euphorbiaceae) in the United States: evaluating CLIMEX predictions with field trials. *Glob Change Biol* 14:813–826
- Ray JD, Sinclair TR (1997) Stomatal closure of maize hybrids in response to drying soil. *Crop Sci* 37:803–807
- Ray JD, Samson BK, Sinclair TR (1997) Vegetative growth and soil water extraction of two maize hybrids during water deficits. *Field Crops Research* 52:135–142
- Rem-Aapresid (2012). <http://www.aapresid.org.ar/rem/cualeson-y-donde-estan-las-malezas-resistentes/>
- Satorre EH, Ghersa CM, Pataro AM (1985) Prediction of *S. halepense* (L.) Pers. rhizome sprout emergence in relation to air temperature. *Weed Res* 25:103–109
- Scaife A, Cox EF, Morris GEL (1987) The relationship between shoot weight, plant density and time during the propagation of four vegetable species. *Ann Bot* 59:325–334
- Scopel AL, Ballaré CL, Ghersa CM (1988) Role of seed reproduction in the population ecology of *S. halepense* in Maize crops. *J Appl Ecol* 25:951–962
- Scott HD, Geddes RD (1979) Plant water stress of soybean (*Glycine max*) and common cocklebur (*Xanthium pensylvanicum*): a comparison under field conditions. *Weed Sci* 27:285–289
- Stuart BL, Krieg DR, Abernathy JR (1985) Photosynthesis and stomatal conductance responses of Johnsongrass (*Sorghum halepense*) to water stress. *Weed Sci* 33:635–639
- Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CM, Powles SB (2007) Evolution of glyphosate-resistant Johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. *Weed Sci* 55:566–571
- Vitta JI, Leguizamón ES (1991) Dynamics and control of *S. halepense* (L.) Pers. shoot populations: a test of a thermal calendar model. *Weed Res* 31:73–79
- Warwick SI, Black ID (1983) The biology of Canadian weeds.61: *S. halepense* (L.) Pers. *Can J Plant Sci* 63: 997–1014
- Warwick SI, Thompson BK, Black LD (1984) Population variation in *Sorghum halepense* Johnsongrass at the northern limits of its range. *Can J Bot* 62:1781–1790
- Yang YW, Newton RJ, Miller FR (1990) Salinity tolerance in Sorghum. II. Cell culture response to sodium chloride in *S. bicolor* and *S. halepense*. *Crop Sci* 30:781–785
- Young KE, Schrader TS (2007) Chapter 13: spatial distribution and risk assessment of Johnson grass (*Sorghum halepense*) in Big Bend National Park. In: KE Young, TS Schader, KG Boykin, C Caldwell, GW Roemer (eds) *Early detection of invasive plants in Big Bend National Park: remote sensing and GIS strategies*. USGS status and trends of biological resources program. Final report, pp 154
- Ziska LH (2003) Evaluation of yield loss in field sorghum from a C₃ and C₄ weed with increasing CO₂. *Weed Sci* 51:914–918