Predictions for Weed Resistance to Herbicides in Brazil: A Botanical Approach

André Andres, Germani Concenço, Fábio Schreiber,
Dirceu Agostinetto, Leandro Vargas, João Behenck,
Giovanni Antoniaci Caputo and
Ygor Sulzbach Alves

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Abstract

The intensive use of herbicides in agriculture has led to the appearance of resistant weed biotypes. Resistance is the inherited ability of a plant to survive following application of an herbicide dose which should be lethal. Morphophysiological weed traits help defining the risk to evolve resistance. These traits are not exclusive to the species but may be innate to botanical order, family, or genus. Four reference countries were screened about the nature of resistance—Australia, Canada, France, and the United States—and the data were used for predictions in the Brazilian scenario. Most weed species with resistant biotypes in the reference countries seem to be native to the continent. The most important botanical families with resistant biotypes in the reference countries were also among the first ones to develop resistance in these countries. There was a predominance of C3 species over C4 in the number of plant species with resistant biotypes in the reference countries. In Brazil, three orders are considered as high risk (Gentianales, Lamiales, and Solanales), besides the six already present. Furthermore, eight botanical families present superior risk to evolve resistance and for five of them (Caryophyllaceae, Polygonaceae, Rubiaceae, Convolvulaceae, and Solanaceae), resistance cases have not been reported to date in Brazil.

Keywords: weed species, botanical traits, herbicide, plant selection, carbon metabolism

1. Introduction

The successive and intensive cultivation of the same crop species in Brazil, with practically no crop rotation, is leading to an increase in the presence of weeds [1]. One should emphasize that the term "weed" had effectively no botanical meaning, since by the classical definitions, a plant can be a "weed" in a given situation while it may be desirable in another. Distinct plant species included into the same botanical order may be considered as weed or desirable. Furthermore, the same species may be considered as a "weed" into an arable field while it can be desirable in gardens, for instance, where they are usually considered as "beneficial weeds" [2].

The use of herbicides for weed control in Brazilian agriculture has increased significantly in the last years, due to a series of factors, such as the growing difficulty to find human labor for manual weeding and the excessive damage caused to plants when adopting in-crop mechanical control [2]. Moreover, the chemical control represents an easy and efficient approach for weed control and therefore farmers are most prone to use this method despite of the other weed suppression strategies [1].

Weed species that have been indirectly selected for adverse conditions obtain their vital elements more efficiently by extracting water, nitrogen, phosphorus, and potassium, respectively, four, five, three, and six times more than crop plants [3]. Thereby, due to their ability to compete for environmental resources with cultivated plants, it is essential to eliminate them from cropping fields. Considering also that usually for every crop there is specific companion weeds [4], weed control based solely on herbicides tends to reduce quickly their efficiency due to plant selection which become resistant or tolerant to these compounds [1]. Compared to other pests, weeds have longer reproduction cycles [5] and produce propagules which survive in soil for several years [1]. These factors contribute to the relatively slow evolution of resistant weeds compared to other pests.

Weed resistance to herbicides is defined as the inherited ability of a plant to survive following application of the commercially used dose of the herbicide recommended for its control. This dose, in regular conditions, should be able to control that weed species [2]. There are several factors responsible for selecting resistant weed biotypes, as the selection pressure imposed by the herbicide [1]. Herbicides differ in the risk that they present to select a given resistant weed biotype, and this depends, among other aspects, on its specificity in terms of point of action into the plant; more specifically the local of action [6].

For instance, the herbicide 2,4-D, is a synthetic auxin used continuously since 1948 and the first case of resistance to this compound was reported only in 1957 [6]. Currently, 40 years later, resistance cases to synthetic auxins was documented only for 14 species in 11 countries [1]. Thus, herbicides from this mode of action and other inhibitors, such as Protox and EPSPs inhibitors, are examples of "low-risk" herbicides for resistance evolution [1, 7]. On the other hand, herbicides like the ones included in the acetolactate synthase (ALS)-inhibiting group are considered as "high risk" for herbicide resistance evolution. This classification for a new resistance case to appear is based on the location in which the herbicide acts into the plant and other aspects [7]; more specifically, its mechanism of action, as a single mutation into the plant, could turn it resistant to the herbicide [6]. The time required for the appearance of the first resistant biotype to commonly used herbicides worldwide from their introduction in the market are shown in **Table 1**.

Herbicide or mode of action	Introduction to the market	First resistance report	Introduction to first case (years)	Location
2,4-D	1948	1957	9	USA and Canada
Triazines	1959	1970	11	USA
Propanil	1962	1991	29	USA
Paraquat	1966	1980	14	Japan
EPSPs inhibitors	1974	1996	22	Australia
ACCase inhibitors	1977	1982	5	Australia
ALS inhibitors	1982	1984	2	Australia

Source: adapted from Agostinetto and Vargas [6].

Table 1. Time required for appearance of the first resistant weed biotype following introduction of a new herbicide mechanism of action into the market.

The history and concepts about weed resistance have been widely explored in the literature including topics dealing with the mechanisms conferring resistance and herbicide traits which most easily select resistant biotypes. Although weed resistance is a well-known problem and is relatively characterized, its occurrence is constantly increasing in a worldwide basis. To assist researchers to keep updated about herbicide resistance spread around the world, there is a website, www.weedscience.org, which is used as a platform for researchers to register the new cases of weed resistance [8]. This website is maintained by the Global Herbicide Resistance Action Committee and CropLife International, and it is an open access tool. The basic world-wide data about weed resistance used in the present study were obtained from that site, which were used with permission from the owners. Further data to botanically characterize the weed species listed on the WeedScience website were obtained from specialized literature.

Besides herbicide risk and frequency of application to the field, which are already well studied in the literature related to the weed science, other plant traits could turn them resistant to herbicides. Morphophysiological characteristics as dormancy behavior, number of seeds produced, annual distribution of emergence, and several others [1] can maximize the chance for the occurrence of weed species in the fields at the time of herbicide application, thus exposing them to the selection pressure imposed by the herbicide [7]. These traits can be studied as not being exclusive for the plant species but a characteristic innate to the botanical order, family, or genus of the weed species with resistant biotypes. Supposing this relationship exists, plants which are most closely related to resistant species could also be most prone to evolve resistance. The present study is based upon this hypothesis.

In order to have a wider comprehension about the path resistance takes into the botanical classification of weed species, from the appearance of the first resistant species to the current situation of resistance in Brazil and its most probable future, four reference countries were selected to serve as background for understanding the Brazilian context of weed resistance and new future resistance cases. The countries with higher number of resistant weed biotypes were first selected; in the second stage of selection were selected among these countries two that represented the American Continent, where Brazil is located; one which represented Europe, from where some weed species are known to be introduced in Brazil, and one to represent Oceania,

where the climate is more alike to the observed in several regions of Brazil. In this context, the following countries were selected to be studied: Australia, Canada, France, and the United States.

2. Chemical classification of resistance

Taking into account the herbicides' mechanisms of action, it is possible to clearly observe a predominance in cases of resistance to the application of the acetolactate synthase (ALS)-inhibiting herbicides in Australia, Canada, and the United States (**Figure 1**), followed by resistance to PSII-inhibiting herbicides in France. The number of resistance cases to PSII-inhibiting herbicides is also high in the other countries, rating this mechanism of action in the second place in number of reported resistance cases in the United States and Canada. In Australia, the number of resistance cases to ACCase and EPSPs herbicides was in the second place, followed by the PSI and PSII herbicides (**Figure 1**).

In comparison to other mechanisms of action, resistance cases to ACCase-inhibiting herbicides were very important in all countries. Moreover, EPSP herbicides were also important in Australia and the United States, but, in general, the number of resistance cases to this mechanism of action was smaller in Canada and France (**Figure 1**). Overall, there were
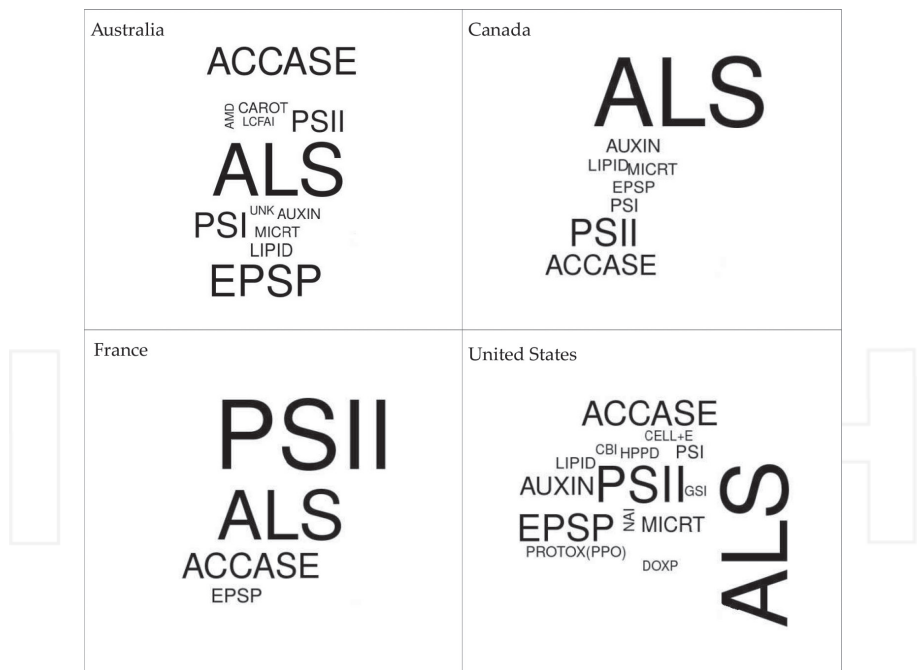

Figure 1. Wordcloud for the occurrence of weeds resistance as a function of mechanism of action in the reference countries. The scale of the font represents the importance of the mechanism compared to the others in the same figure. Source: adapted from Heap [8].

weeds resistant to 12, 8, 4, and 14 herbicidal mechanisms of action, respectively, in Australia, Canada, France, and the United States (**Figure 1**).

To date (November 2016) in Brazil, there are cases of weeds resistant to five mechanisms of action (**Figure 2**). Furthermore, the majority of these cases is associated with ALS herbicides. In the second place comes the resistance against EPSPs, followed by ACCase, Auxin, and Protox herbicides. Compared to other countries, one may observe that the order of importance of herbicide mechanisms of action in Brazil resembles more closely to the Australia and the United States context (**Figure 1**). The number of resistance cases to ACCase herbicides is similar to Canada; however, resistance to EPSP herbicides is not as important in that country as compared to Brazil. Moreover, the number of resistance cases to each mechanism of action in France was the one that contrasted the most from Brazil (**Figure 1**).

France is characterized by growing large areas of barley, to supply the demand of breweries [9, 10], and oat. Maize is also a common crop in France, where the French production of these crops, potatoes and sugarbeets, helps to meet the demand of these products in Europe [9]. In the cooler regions of France, apples are cultivated, as well as grapes for the production of wine [10]. Other French crops mostly include plums, tomatoes, and peaches [9].

The Brazilian agriculture differs from French crops as it is based mostly on maize, wheat, rice, soybeans, orange (*in natura* and juice), sugarcane (including sugar and ethanol), cotton, cassava, coffee, potatoes. Fruits such as grapes, apples, bananas, mangoes, melons, tobacco, papaya, and
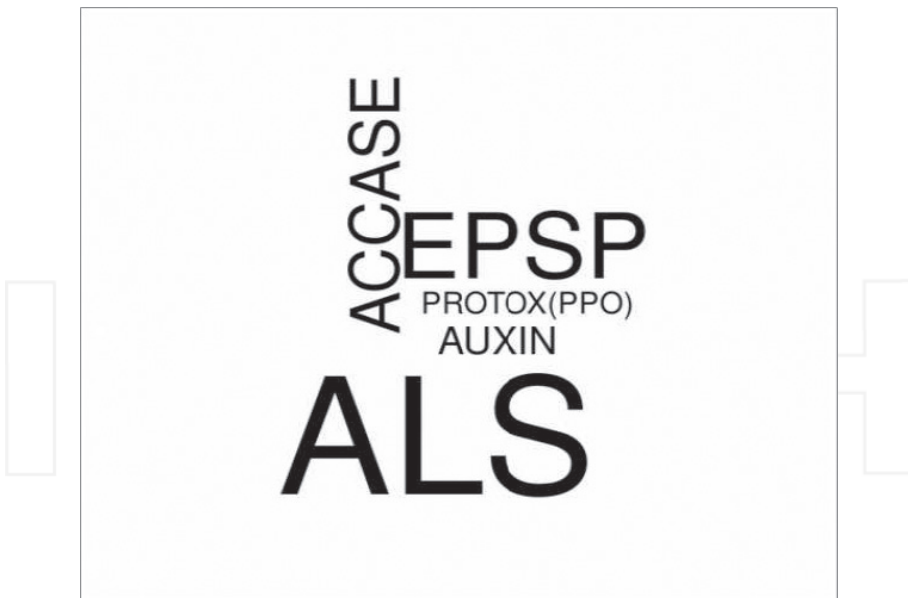

Figure 2. Wordcloud for the occurrence of weeds resistance as a function of mechanism of action in Brazil. The scale of the font represents the importance of the mechanism compared to the others in the same figure. Source: adapted from Heap [8].

pulp are also cultivated. Moreover, the paper industry is also important in the country [11]. As the world's sixth largest economy, Brazil ranks third among the world's major agricultural exporters and fourth for food products, being the world's largest producer and exporter of products such as soybean, coffee, sugarcane, orange juice, meat, and tobacco [12].

Thus, there is a great difference between the major crops grown in France and Brazil, which is probably the cause for a distinct herbicide demand and, as consequence, the difference in nature of resistance cases between these two countries.

3. Botanical classification of resistance

The botanical classification of life forms is very often, if not always, a challenge for agronomists. In order to understand how nature is reacting to the heavy load of herbicides continuously thrown into the environment, first there is a need to briefly understand the botanical classification and how plants are grouped.

The Biological Classification—or Taxonomic Rank—describes the level of a group of organisms into the taxonomic hierarchy [13]. The main taxonomic ranks are domain, kingdom, division, class, order, family, genus, and species, all of them with an internal classification prefixed by "sub" (subclass, subfamily, etc.) [14]. Other classification levels into each section may exist, but this is beyond an agronomist's point of view and will not be discussed in the present study.

3.1. Botanical order

In botany, "order" is a taxonomic rank located between "class" and "family," grouping plants with similar traits at a certain degree [14]. Even though several botanical orders exist, most weed species should be classified into approximately 20 orders. **Figure 3** depicts weed species distribution into orders, from combined data of the five studied countries (Australia, Brazil, Canada, France, and the United States).
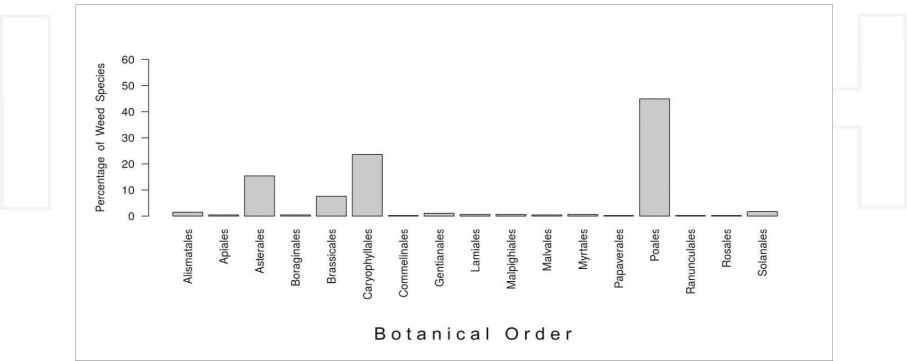

Figure 3. Percentage of resistant weed species by botanical order, with pooled data from the five studied countries. Source: adapted from Heap [8].

The great majority of weed species resistant to herbicides are included into the orders Poales, Caryophyllales, Asterales, and Brassicales (**Figure 3**). For the four reference countries (**Figure 4**), the order Poales was the predominant one, as also seen for the overall order data (**Figure 3**). In Canada, the importance of this order was shared with Caryophyllales, which was the second most important resistant weed group in France. Asterales was of importance also in Australia and the United States while it was of secondary importance in Canada and France (**Figure 4**). Overall, 10, 8, 6, and 12 orders including resistant weed species were identified in Australia, Canada, France, and the United States, respectively.

In Brazil, the most important weed species are included into the botanical orders Poales, Asterales, and Caryophyllales (**Figure 5**). In general, these findings are according to the data observed for the four reference countries (**Figure 4**), where these three botanical orders also tended to predominate.

There are five, four, three, and six botanical orders, respectively, in Australia, Canada, France, and the United States, with resistant biotypes (**Figure 4**), which still absent in Brazil (**Figure 5**). Among the plant orders with resistant biotypes, Solanales is present in the four reference countries, whereas Lamiales and Gentianales are present in Australia and Canada (**Figure 4**). The order Solanales includes botanical families with important weed species in Brazil like Solanaceae and Convolvulaceae; Lamiales includes the families Plantaginaceae and Lamiaceae, while Gentianales includes the family Rubiaceae [14].
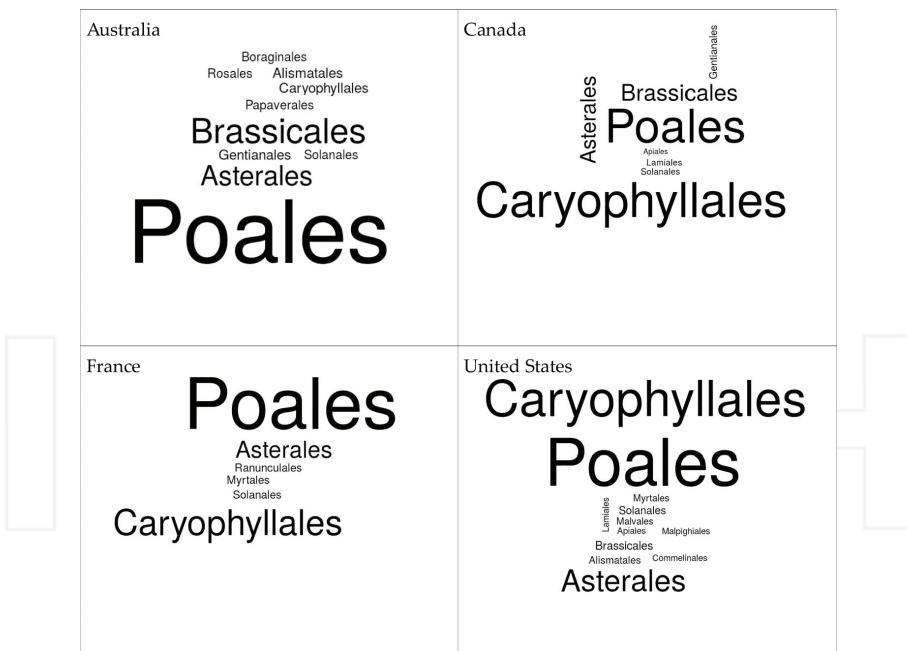

Figure 4. Wordcloud for the occurrence of weed resistance as a function of botanical order in the reference countries. The scale of the font represents the importance of the order compared to the others in the same figure. Source: adapted from Heap [8].
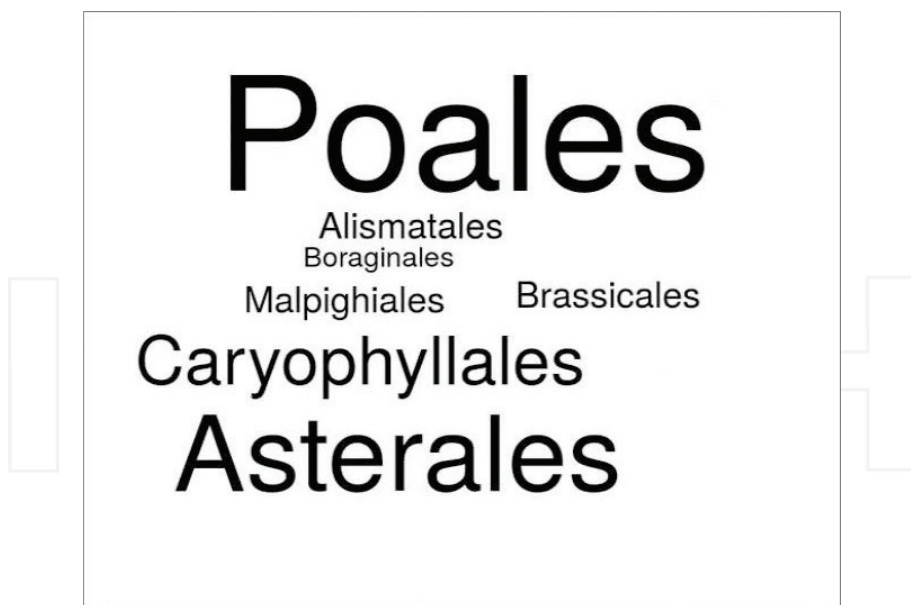
Figure 5. Wordcloud for the occurrence of weed resistance as a function of botanical order in Brazil. The scale of the font represents the importance of the order compared to the others in the same figure. Source: adapted from Heap [8].

It should be emphasized that in the present study, the classification of weeds in botanical orders is restricted to those species considered as "weed" in the agricultural context; this does not mean at all major number of plant species included in that order are most prone to become a weed. This relationship is yet to be established, supposing it exists.

3.2. Botanical family

Resistant weeds grouped by botanical family (**Figure 6** and **Figure 7**) showed Poaceae as the major family with resistant species for all studied countries, including Brazil. In Australia, Brassicaceae and Asteraceae families were in the second and third places, respectively; in Canada, Amaranthaceae was the family with the most number of plant species with resistant biotypes to herbicides followed by Brassicaceae, Asteraceae, and Chenopodiaceae (**Figure 6**). In France, Asteraceae, Amaranthaceae, and Polygonaceae were also important botanical families in number of weeds with resistant biotypes, and in the United States, Amaranthaceae and Asteraceae were highlighted after Poaceae (**Figure 6**).

In Brazil, Asteraceae and Amaranthaceae were the predominant families of plants with resistant weed biotypes after Poaceae (**Figure 7**).

Compared to the reference countries, from one point of view, there is danger in Brazil—under the current panorama of herbicides use and weed management—for an increase in the
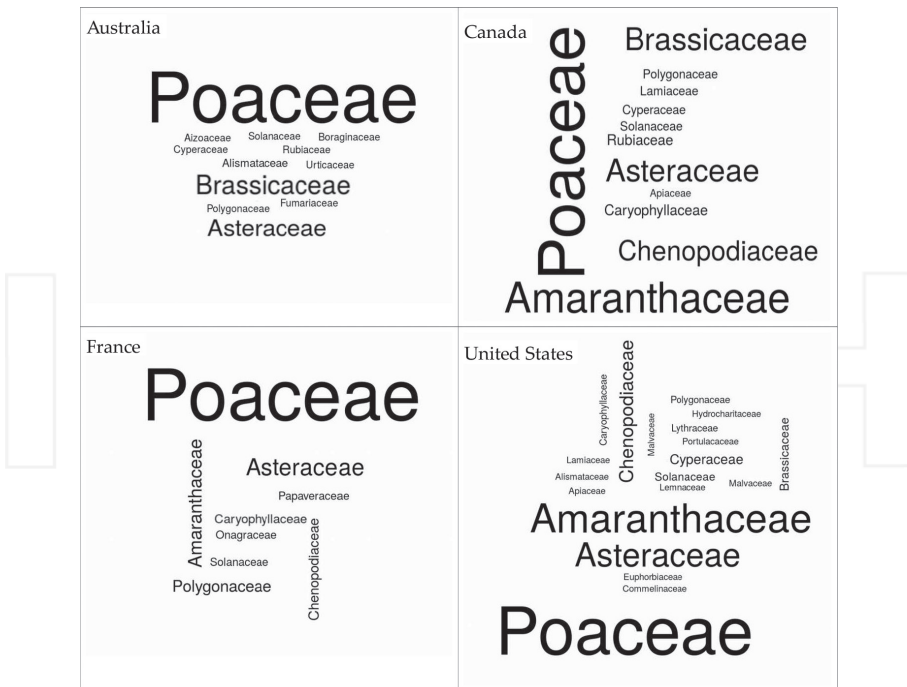
Figure 6. Wordcloud for the occurrence of weed resistance as a function of botanical family in the reference countries. The scale of the font represents the importance of the family compared to the others in the same figure. Source: adapted from Heap [8].

number of resistant plant biotypes mainly from the families Asteraceae, Amaranthaceae, and Brassicaceae, which are significant in the reference countries and, at the same time resistant, biotypes were already reported in Brazil.

Second, there is also a great chance for the appearance of resistant weed biotypes from families which are absent in the current Brazilian scenario, but which have great importance in all four reference countries, like Polygonaceae and Solanaceae, or in three out of the four reference countries like Chenopodiaceae and Caryophyllaceae (**Figure 6**).

A third scenario leads to the increasing number of multiple resistance or the appearance of resistance to a second herbicidal mechanism of action in weed species which are already resistant to a given mechanism of action [6]. This is concerning due to the nature of the new technologies of crop tolerance to herbicides, the so-called "all-in-one" tolerance; crops will have tolerance to more than one herbicide mechanism of action [15]. Thus, weeds will have to "tolerate" or "resist" to most of the herbicides associated to each technology, in order to prevail in arable fields.

One should note that there was an initial attempt to predict future cases of weed resistance in Brazil [16], by analyzing the herbicidal mechanism of action to which some plant

Figure 7. Wordcloud for the occurrence of weed resistance as a function of botanical family in Brazil. The scale of the font represents the importance of the family compared to the others in the same figure. Source: adapted from Heap [8].

species evolved resistance in some parts of the world, and relating the risk for new cases to the adoption of such herbicides in Brazilian agriculture. This analysis [16] was, however, excluded in the updated version of the same book [15] but may be considered as complementary to the present study, even being outdated by some degree.

When the evolution of appearance of families with resistant biotypes was analyzed by countries (**Figure 8**), it was observed that the most important botanical family in number of resistance cases is Poaceae (**Figure 6** and **Figure 7**), which was the first to appear in Australia, in 1982; the second in France and the United States in 1978 and 1970, respectively; and the sixth botanical family to have resistant biotypes in Canada (**Figure 8**).

The other botanical families with resistant biotypes with great importance that were reported in the reference countries (**Figure 6**) are listed in the inset table in **Figure 8**. It is important to note that the most important botanical families were also, in general terms, between the first ones to appear in the respective countries. This leads to the hypothesis that these families are of relatively recent evolutionary origin [5]. There is evidence that the preponderance of weeds from relatively recent evolutionary origin indicates the trend to an increasing of troublesome, highly adaptable weeds in agriculture [5, 7]. An example is the botanical family Asteraceae [7], which already has resistant biotypes in the five countries studied here (**Figure 5** and **Figure 7**). Thereby, in the years to come, Brazil may

Figure 8. Evolution of resistant botanical families by year and country, with an inset table showing the number of families in each reference country with resistant biotypes, and the number of these families that are present in Brazil, with or without resistant biotypes. Source: adapted from Heap [8].

experience an increase in the occurrence of weed species from families with recent evolutionary origin.

Figure 9 illustrates the geographic distance between Brazil and the reference countries used in this study. In general terms, half or less than half of the families present in the reference countries are also present in Brazil with resistant biotypes. This may lead to the assumption that there is still plenty of species to evolve resistance in Brazil, supposing that farmers and technicians will keep relying heavily on the chemical weed control, in absence of alternative weed management techniques.

Figure 9. Correlation in the occurrence of botanical families of weeds between Brazil and the reference countries, and its proportion of families which already present resistant biotypes in Brazil. Source: adapted from Heap [8].

3.3. Botanical genera

The botanical genera with resistant species in the reference countries are shown in **Figure 10**. In Australia, *Lolium* was the predomi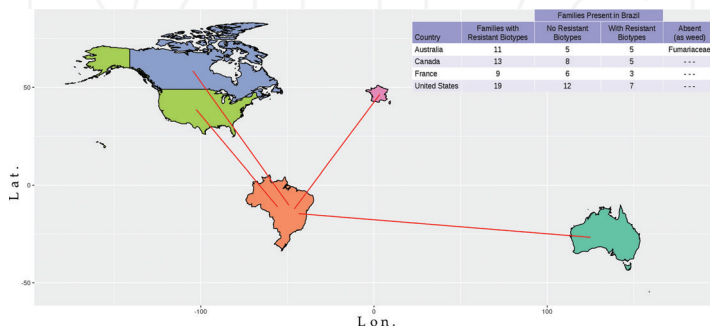nant genus in number of resistant weed species; in Canada and the United States, *Amaranthus* is the most important one; in France, there is no predominant genus with the most cases of resistant weed biotypes being *Avena, Amaranthus, Lolium, Setaria,* and *Echinochloa* similar in importance (**Figure 10**). In Australia, *Raphanus, Bromus, Hordeum, Avena,* and *Sisymbrium* are the second most important group of genera with resistant weed biotypes; in Canada, *Setaria* and *Avena* are also in the second group. In the United States, a great number of botanical genera with resistant weed biotypes occur, but *Echinochloa, Conyza, Poa, Setaria, Kochia, Ambrosia,* and *Lolium* may be highlighted in a second group of importance, following *Amaranthus*.

In Brazil, 19 genera with resistant biotypes are reported (**Figure 11**), where *Amaranthus, Conyza,* and *Bidens* are the most important ones, followed by *Digitaria, Lolium,* and *Echinochloa* in the second group. A third group includes *Sagittaria, Euphorbia, Eleusine, Cyperus,* and *Raphanus*.

Figure 10. Wordcloud for the occurrence of weed resistance as a function of botanical genus in the reference countries. The scale of the font represents the importance of the genus compared to the others in the same figure. Source: adapted from Heap [8].
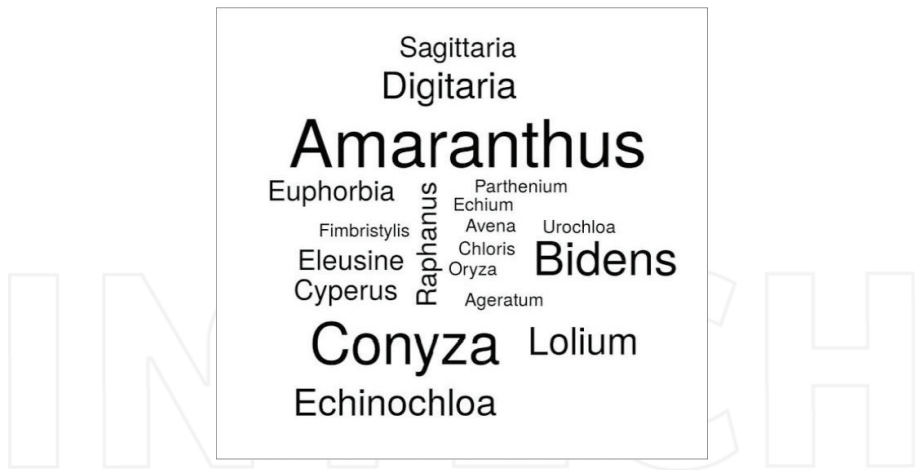
Figure 11. Wordcloud for the occurrence of weed resistance as a function of botanical family in Brazil. The scale of the font represents the importance of the genus compared to the others in the same figure. Source: adapted from Heap [8].

4. Botanical class and carbon metabolism pathway

As mentioned earlier, plant taxonomy is not static, and from time to time some adaptations are proposed to plant nomenclature by different authors [17], trying to adjust plant classification under the light of new evolutionary evidences or simply aiming to rearrange previous taxonomic trees. Angiosperms are, in a free definition, plants with flowers whose seeds are protected in fruits [13, 18]. Along the history, different plant classification systems were proposed, which can be roughly divided into three groups: (1) artificial systems, based on superficial features; (2) natural systems, based on form relationships; and (3) phylogenetic systems, based on evolutionary and genetic relationships [18].

The artificial systems are very old, based usually on a single character, and have been used as example by Theophrastus (370 285 BC) and Linnaeus (1707 1778 AD); natural systems were based on a set of botanical characters, being used in the eighteenth and nineteenth centuries; examples are the classification systems of Jussieu and Bentham & Hooker [19]. Among the phylogenetic systems, Cronquist [20], later reviewed in 1988 [21], is one of the most used, and it divides flowering plants into two classes: (1) Magnoliopsida (dicotyledons, dicots) and (2) Liliopsida (monocotyledons, monocots). With no intention to start a war among plant taxonomists and considering the division into these two classes is the most common in the weed science, we grouped resistant plant species into dicots and monocots (**Figure 12** and **Figure 13**).

Australia has 34 dicot species with resistant biotypes, while 54 monocot weed species had at least one resistant biotype (**Figure 12**). Monocot species were also the majority in France, where 20 dicots and 26 monocots had at least one resistant biotype. In the northern region of the American continent, dicots predominated among the species with resistant biotypes; 59 and 108 dicots contrasted with 31 and 87 monocots, in Canada and the United States, respectively (**Figure 12**).
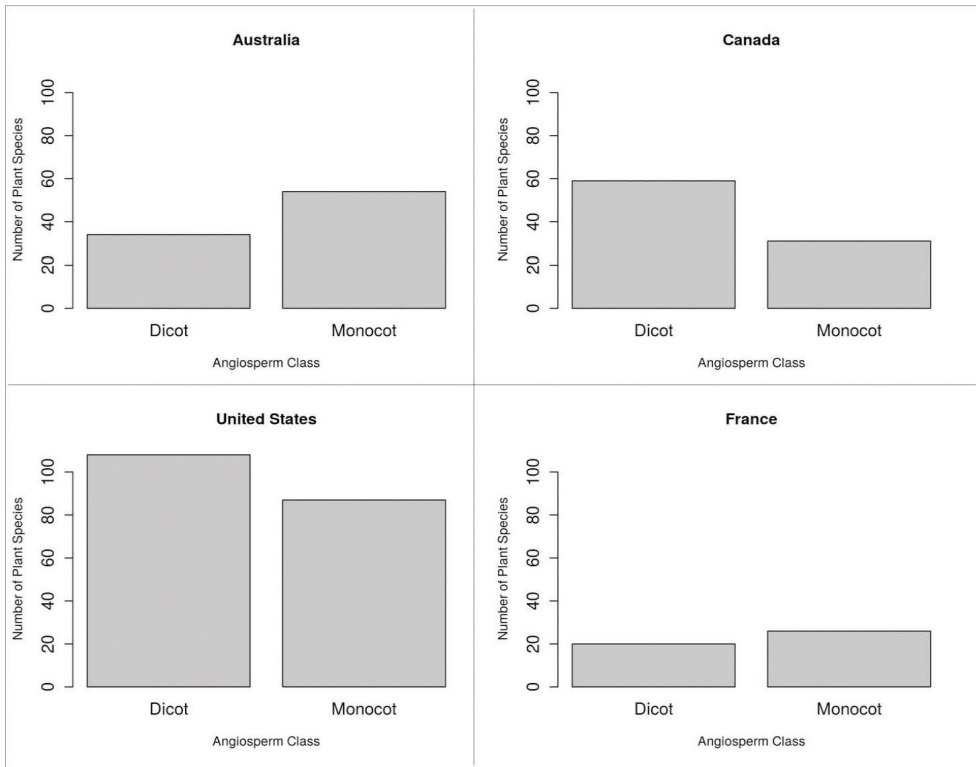
Figure 12. Occurrence of weed resistance as a function of botanical class in the reference countries. Source: adapted from Heap [8].

When weed species with resistant biotypes were grouped in the reference countries by the carbon metabolism (C3, C4, intermediary/hybrid/unknown) (**Figure 13**), there was a clear predominance of C3 species over C4 in the number of plant species with resistant biotypes for all countries; 75, 49, 115, and 25 weed species with at least one biotype resistant to herbicides were C3, while only 5, 31, 71, and 14 were C4, respectively, for Australia, Canada, the United States, and France (**Figure 13**).

Plant species with carbon metabolism by the C4 cycle, in evolutionary terms are derived from the C3 cycle [22]; furthermore, although it is generally claimed that C4 plant species are most widely distributed in warmer and dry environments compared to C3 plants, this is not remarkable since C4 plants evolved to optimize carbon fixation in low-C environments, and not essentially to resist to water stresses as usually believed [23]. In fact, C4 plants may be equally or even more sensitive to water stress than C3 species, in spite of the greater water use efficiency of C4 plants [24].

In Brazil, where the majority of the arable territory is located in warm climates with mild winters, there were no significant differences in the proportion of dicots (22) and monocots (20) with resistant biotypes (**Figure 14**). In North America (Canada and the United States), dicot
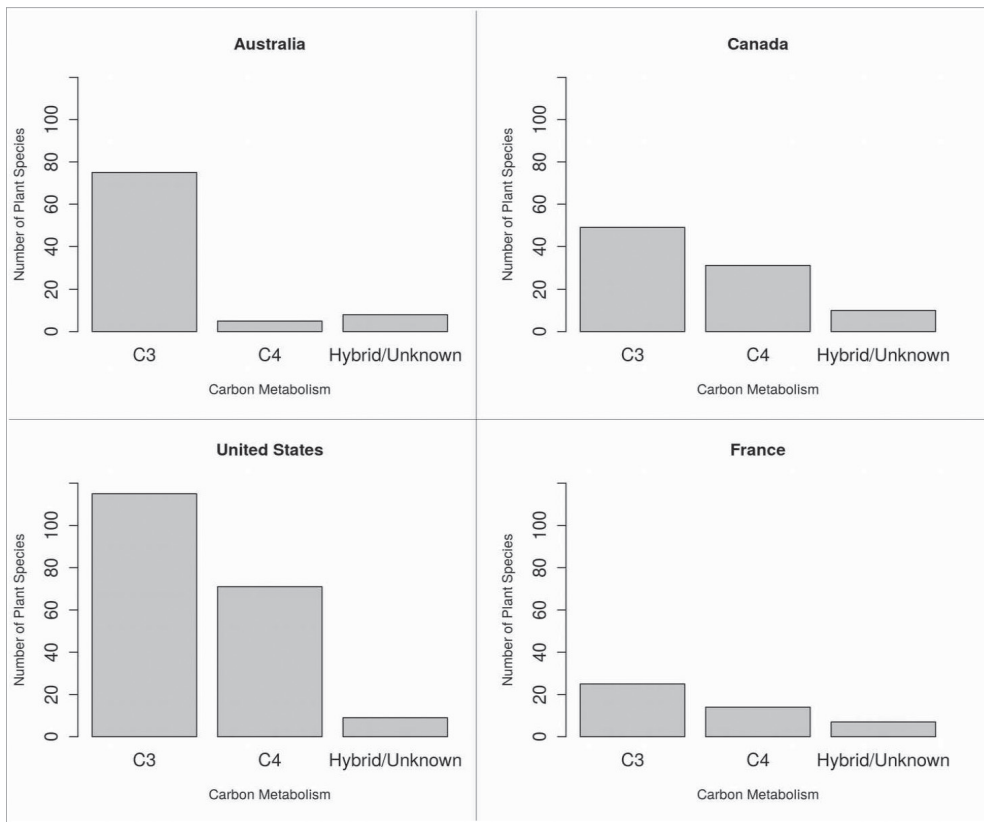
Figure 13. Occurrence of weed resistance as a function of carbon metabolism pathway in the reference countries. Source: adapted from Heap [8].

weed species with resistant biotypes predominated, while in France and Australia, monocots tended to predominate (**Figure 13**).

Dicot species may have advantages over monocots. With no intention to differentiate these two groups of plants, some traits from each group may be highlighted: first, the vascular bundle of dicots may allow flow of higher volumes of sap to and from leaves, as well as up and down into the plant compared to monocots; second, the stronger vascular bundle could allow dicots to resist stronger water potentials, which could be advantageous in both rich and scarce water environments; third, the two cotyledons could allow for higher photosynthesis rates to dicots, which would depend less on the seed stored energy to form its initial leaf area, increasing their chance of survival [22]. These facts could help explain why dicots were superior to monocots in Canada and the United States. On the other side, bulliform cells which are present in many monocots—not only in grasses—may help avoiding stress by excessive light incidence in low latitude environments [23, 24], which could turn it into a big advantage for some groups of monocots in tropical agriculture.
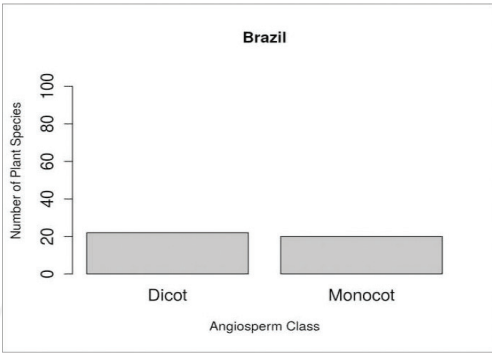
Figure 14. Occurrence of weed resistance as a function of botanical class in Brazil. Source: adapted from Heap [8].

There was also no difference in the proportion of plants as a function of the carbon metabolism pathway (**Figure 15**). Ehleringer and Monson [23] report that in anthropogenically altered environments, C4 plants are usually not so advantageous over C3. In the reference countries (**Figure 13**), most weed species with resistant biotypes were C3, but in Brazil (**Figure 15**) this difference was not remarkable. By considering this, one may hypothesize that in Brazil most of the arable lands are as intensely explored as consequence of the anthropogenic effect, that it led C4 plants to almost totally lose their superior potential compared to C3 weeds in the same environment.

When the data of angiosperm class is crossed with the data of carbon metabolism pathway (**Figure 16**), visually there appears to be little to no relationship between these factors; but when we apply a X^2 test to the data *Ang.Class* x *Carb.Metab*, (*Dic./Mon.* vs. *C3/C4* only), it turns out to be significant at 5% probability for all countries, except the United States (**Figure 16**). This supplies initial evidence that C3 and C4 species with resistant biotypes to herbicides may not be equally distributed into dicots and monocots. In Brazil (**Figure 16**), most dicots are C3
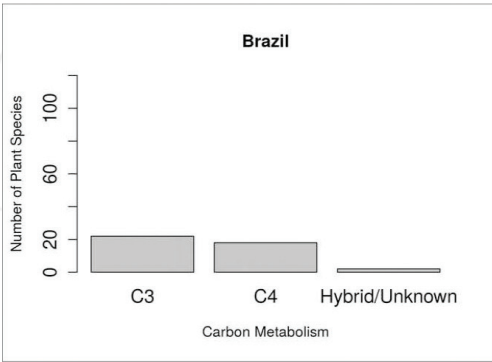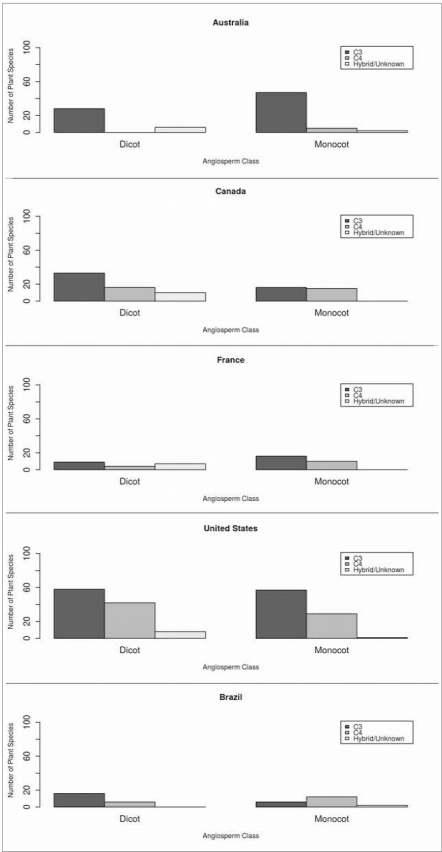

Figure 15. Occurrence of weed resistance as a function of carbon metabolism pathway in Brazil. Source: adapted from Heap [8].

while most monocots with resistance to herbicides are C4; for Australia and France, C3 species also predominate in the monocot class, while in Canada the proportion of C3 and C4 species with any biotype resistant to herbicides is equivalent (**Figure 16**).

In other words, it appears that the dicot class of angiosperms is significant (four out of four) for presenting a higher number of C3 species with resistant biotypes compared to C4. For monocots, Australia and France presented higher number of C3 species with resistance; in Canada, this relationship was alike, and in Brazil, there were more C4 monocot species with resistance to herbicides than C3. Anyway, the carbon metabolism pathway (**Figure 13** and **Figure 15**) seems to be the most significant compared to the angiosperm class (**Figure 12** and **Figure 14**). Thus, one would expect more cases of C3 weed biotypes with resistance to herbicides in Brazil (**Figure 15**), compared to the reference countries (**Figure 13**), for dicots (**Figure 16**). For monocots, there will be a need for a follow-up to understand if the tendency of majority in C4 species (**Figure 16**) will be maintained, or if it is only a deviation

Country	Dicots C^3/C_4	Monocots C^3/C_4	$X^2_{p\text{-value}}$
Australia	⬆	⬆	0.021
Canada	⬆	≅	0.018
France	⬆	⬆	0.004
USA	ns ⬆	ns ⬆	0.059
Brazil	⬆	⬇	0.014

Note: the X^2-test only supplies evidence if there is any association between two variables, or alternatively if they are independent. The interpretation presented in this table was subjectively obtained and should be used only as reference.

Figure 16. Occurrence of weed resistance as a function of botanical class and carbon metabolism pathway. Source: adapted from Heap [8].

from the real tendency which will be corrected by nature in the future. One should con-sider the probable loss of superiority from C4 plants over C3 as a consequence of the heavy anthropogenic effect in arable fields, as hypothesized by Ghannoum [24].

5. Geographical region of origin of families with resistant biotypes

The **probable** geographical center of origin of the families with resistant biotypes is sum-marized by the studied country in **Figure 17**. The region of origin for each botanical family is
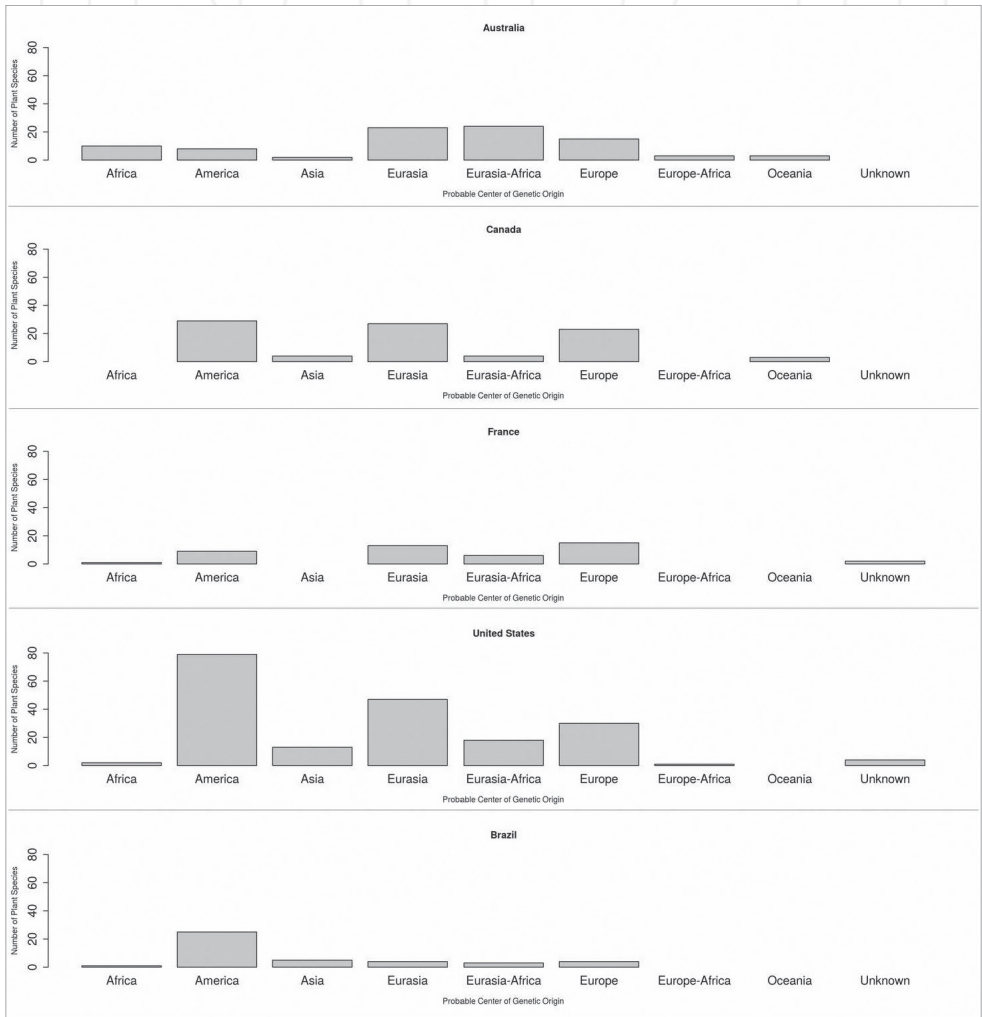

Figure 17. Occurrence of weed resistance as a function of the **probable** geographical region of origin of the genus. Source: adapted from Heap [8].

difficult to be defined, and data is sometimes controversial; thus, **Figure 17** should be inter-preted as an approximation as close as possible to the currently available data about the origin of plant families. Families with higher degrees of uncertainties in their origin were grouped, like "Eurasia," which includes Europe and Asia, Eurasia-Africa (Europe, Asia, Africa), and Europe-Africa.

Most botanical families with resistant weed biotypes in Australia were originated in Eurasia and Africa; in Canada, they came from America and Eurasia (and of course Europe); in France, most weeds with resistant biotypes are native from Europe, and some of them could have come from Asia (Eurasia). In the United States, most families are native from the Americas, while about a half of the species with resistant biotypes came from Eurasia (in **Figure 17**, Asia + Eurasia + Europe data).

Summarizing, half or most of the weed species, which presented resistant biotypes in each of the reference countries, seem to be native to their continent (**Figure 17**), and this makes sense since the center of genetic origin of a given botanical group usually (if not always) presents the greatest genetic variation for that species [25]. Thus, the genetic variation which could result in the appearance and consequent selection of resistant biotypes would probably be most easily present in the genetic center of origin of the plant group. In Brazil (**Figure 17**), the same tendency is observed as most of the plants which presented resistant biotypes were most probably native from the Americas.

6. Most probable Brazilian weed groups to evolve resistance to herbicides

Table 2 shows the main weed species in the Brazilian agriculture [2]. Surely, a great number of significant Brazilian weed species are out of the list, but the most cited ones in the special-ized literature in soybean, corn, cotton, wheat, sugarcane, *Eucalyptus*, citrus, and cassava are included in **Table 2**. Orders and families with gray background are those identified in the reference countries as the most probable ones to contain weed species with superior ability to evolve resistance to herbicides. Genera and species with gray background are those that already present at least one resistant biotype in Brazil.

To date (November 2016), 20 weed species have been reported in Brazil as presenting at least one resistant biotype (**Table 2**). Three plant orders (Gentianales, Lamiales, and Solanales) are considered to contain weed species with superior ability to evolve resistance to herbicides, being these orders complemented by those that already present weed species with resistant biotypes (Asterales, Brassicales, Caryophyllales, Malpighiales, Alismatales, and Poales).

Eight botanical families are considered as presenting superior risk to evolve resistance to herbicides in Brazil (Asteraceae, Brassicaceae, Caryophyllaceae, Polygonaceae, Rubiaceae, Convolvulaceae, Solanaceae, and Poaceae), and five of them (Caryophyllaceae, Polygonaceae, Rubiaceae, Convolvulaceae, and Solanaceae) still do not present any weed species in Brazil with confirmed resistance to herbicides (**Table 2**).

Researchers should be aware, however, not to consider only the data summarized in **Table 2** to collect evidences about future cases of weed resistance in Brazil, as that table included

Class	Order	Family	Genus / species	Common name	Common name (PT)	Main crops
Dicot	Apiales	Apiaceae	*Bowlesia incana*	Hoary bowlesia	Erva-salsa	Wheat
Dicot	Asterales	Asteraceae	*Acanthospermum hispidum*	Bristly starbur	Carrapicho-de-carneiro	Cotton, Citrus
Dicot	Asterales	Asteraceae	*Ageratum conyzoides*	Tropical whiteweed	Mentrasto	Cotton, Citrus
Dicot	Asterales	Asteraceae	*Bidens pilosa*	Hairy Beggarticks	Picão-preto	Cotton, Citrus, Cassava, Soybean, Wheat, Maize
Dicot	Asterales	Asteraceae	*Bidens subalternans*	Greater Beggarticks	Picão-preto	Cotton, Wheat
Dicot	Asterales	Asteraceae	*Conyza spp.*	Hairy Fleabane	Buva	Cotton, Eucaliptus, Cassava, Citrus, Soybean, Wheat
Dicot	Asterales	Asteraceae	*Emilia sonchifolia*	lilac tasselflower	Falsa-serralha	Citrus, Cassava
Dicot	Asterales	Asteraceae	*Galinsoga parviflora*	Gallant soldier	Picão-branco	Citrus, Wheat
Dicot	Asterales	Asteraceae	*Parthenium hysterophorus*	Ragweed parthenium	Losna-branca	
Dicot	Asterales	Asteraceae	*Sonchus oleraceus*	Sow thistle	Serralha	Citrus, Wheat
Dicot	Asterales	Asteraceae	*Synedrellopsis grisebachii*	Straggler daisy	Agriãozinho	Citrus, Eucaliptus
Dicot	Asterales	Asteraceae	*Tridax procumbens*	Coatbuttons	Erva-de-touro	Citrus, Eucaliptus
Dicot	Brassicales	Brassicaceae	*Raphanus* spp.			Cassava, Wheat, Maize
Dicot	Caryophyllales	Amaranthaceae	*Alternanthera tenella*	Parrotleaf	Apaga-fogo	Cotton
Dicot	Caryophyllales	Amaranthaceae	*Amaranthus spp*		Caruru	Cotton, Sugarcane, Citrus, Maize, Cassava
Dicot	Caryophyllales	Caryophyllaceae	*Stellaria media*	Common chickweed	Erva-de-passarinho	Wheat
Dicot	Caryophyllales	Polygonaceae	*Rumex* spp		Língua-de-vaca	Wheat
Dicot	Caryophyllales	Portul acaceae	*Portulaca oleracea*		Beldroega	Cassava, Sugarcane, Citrus
Dicot	Cucurbitales	Cucurbitaceae	*Luffa aegyptiaca*	Spongegourd	Bucha	Sugarcane
Dicot	Cucurbitales	Cucurbitaceae	*Momordica charantia*	Bitter melon	Melão-de-são-caetano	Sugarcane

Class	Order	Family	Genus / species	Common name	Common name (PT)	Main crops
Dicot	Fabales	Fabaceae	*Aeschynomene spp.*		Angi quinho	Rice
Dicot	Gentianales	Rubiaceae	*Borreria verticillata*	Buttonweed	Vassoura-de-botão	Cotton
Dicot	Gentianales	Rubiaceae	*Richardia brasiliensis*	Brazilian calla-lily	Poaia-branca	Citrus, Maize, Wheat
Dicot	Gentianales	Rubiaceae	*Spermacoce latifolia*	Malayalam	Erva-quente	Citrus, Eucaliptus
Dicot	Lamiales	Boraginaceae	*Echium plantagineum*	Patersons curse	Flor roxa	Wheat
Dicot	Malpighiales	Euphorbiaceae	*Euphorbia heterophylla*	Wild Poinsettia	Leiteiro	Cotton, Sugarcane, Cassava, Maize, Soybean, Wheat
Dicot	Malvales	Malvaceae	*Sida* spp.	Sida	Guanxuma	Cassava, Wheat, Sugarcane, Maize
Dicot	Myrtales	Onagraceae	*Ludwigia longifolia*	Primrose willow	Cruz-de-malta	Rice
Dicot	Solanales	Convolvulaceae	*Ipomoea spp.*	Morningglory	Corda-de-viola	Cotton, Citrus, Cassava, Soybean, Wheat, Maize
Dicot	Solanales	Convolvulaceae	*Merremia aegyptia*	Hairy merremia	Corda-de-viola	Sugarcane
Dicot	Solanales	Convolvulaceae	*Merremia cissoides*	Roadside woodrose	Corda-de-viola	Sugarcane
Dicot	Solanales	Solanaceae	*Nicandra physalodes*	Apple-of-Peru	Joá-de-capote	Cotton
Dicot	Solanales	Solanaceae	*Solanum americanum*	American black nightshade	Maria-pretinha	Cotton
Dicot	Solanales	Solanaceae	*Solanum viarum*	Tropical soda apple	Joá-bravo	Cotton
Monocot	Alismatales	Alismataceae	*Sagittaria montevidensis*	Giant arrowhead	Chapéu-de-couro	Rice
Monocot	Commelinales	Commelinaceae	*Commelina benghalensis*	Benghal dayflower	Trapoeraba	Cotton, Eucaliptus, Cassava
Monocot	Commelinales	Pontederiaceae	*Heteranthera reniformis*	Kidney leaf mud plantain	Aguapé	Rice
Monocot	Poales	Cyperaceae	*Cyperns spp.*	Sedges	Ciperáceas	Cassava, Sugarcane, Citrus, Rice
Monocot	Poales	Cyperaceae	*Fimbristyllis miliacea*	Fringerush	Cuminho	Rice

Class	Order	Family	Genus / species	Common name	Common name (PT)	Main crops
Monocot	Poales	Poaceae	*Avena sativa*	Wild oat	Aveia	Wheat
Monocot	Poales	Poaceae	*Avena strigosa*	Wild oat	Aveia	Wheat
			Avena fatua	Wild oat	Aveia	
Monocot	Poales	Poaceae	*Brachiaria spp.*	Alexandergrass	Capim-marmelada	Sugarcane, Citrus, Cassava, Maize, Soybean, Wheat, Rice
Monocot	Poales	Poaceae	*Cenchrus echinatus*	Southern sandbur	Capim-carrapicho	Cotton, Citrus, Cassava
			Chloris elata	Tall windmill grass	Capim-branco	
Monocot	Poales	Poaceae	*Cynodon dactylon*	Vilfa stellata	Grama-seda	Sugarcane, Citrus
Monocot	Poales	Poaceae	*Digitayia spp.*	Sourgrass	Capim amargoso	Citrus, Eucaliptus, Cassava, Soybean, Cotton, Maize, Rice
Monocot	Poales	Poaceae	*Echinochha spp*	Barnyardgrass	Capim arroz	Maize, Rice
Monocot	Poales	Poaceae	*Eleusine indica*	Goosegrass	Capim pé-de-galinha	Cotton, Sugarcane, Citrus, Maize, Rice
Monocot	Poales	Poaceae	*Eriochloa punctata*	Louisiana cupgrass	Capim-de-várzea	Rice
Monocot	Poales	Poaceae	*Ischaemum rugosum*	Ribbed muraingrass	Capim-macho	Rice
Monocot	Poales	Poaceae	*Leersia hexandra*	Southern cutgrass	Grama-boiadeira	Rice
Monocot	Poales	Poaceae	*Lolium multiflorum*	Italian ryegrass	Azevém	Eucaliptus, Maize, Soybean, Wheat
Monocot	Poales	Poaceae	*Luziola peruviana*	Peruvian watergrass	Grama-boiadeira	Rice
Monocot	Poales	Poaceae	*Oryza sativa*	Weedy rice	Arroz daninho	Rice
Monocot	Poales	Poaceae	*Panicum dichotomiflorum*	Fall panicgrass	Capim-do-banhado	Rice
Monocot	Poales	Poaceae	*Panicum maximum*	Guinea grass	Capim-colonião	Sugarcane, Citrus, Cassava
Monocot	Poales	Poaceae	*Paspalum modestum*	Water paspalum	Lombo-branco	Rice

Class	Order	Family	Genus / species	Common name	Common name (PT)	Main crops
Monocot	Poales	Poaceae	*Rotboellia exaltata*	Itchgrass	Capim-camalote	Sugarcane
Monocot	Poales	Poaceae	*Sorghum halepense*	Johnson grass	Massambará	Sugarcane

NOTE: Botanical orders and families marked with gray background present superior potential risk of including weed species with resistant biotypes in the future based on the history of the reference countries (Australia, Canada, France and United States). Genus/Species with gray background already include weed species with resistant biotypes in Brazil as of November, 2016.

Table 2. Botanical classification highlighting orders, families and Genus/species of weeds with superior ability to evolve resistance in Brazil.

only a few weed species from the total Brazilian pool of weed species listed by some authors [3, 26–28]. The additional data supplied in the present chapter (herbicide mechanism of action, carbon metabolism, geographical region of origin, etc.) should be also considered together with the list of herbicides available for each crop grown in Brazil, as well as the frequency of application of each herbicide in each crop.

7. Conclusions

Most weed species with resistant biotypes in the reference countries seem to be native to their continent. The most important botanical families with resistant biotypes in the reference countries were also among the first ones to appear in the respective countries. There was predominance of C3 species over C4 in the number of plant species with resistant biotypes in the reference countries. In Brazil, three orders (Gentianales, Lamiales, and Solanales) are considered as high risk, besides the six already present. Furthermore, eight botanical families present superior risk to evolve resistance, and for five of them (Caryophyllaceae, Polygonaceae, Rubiaceae, Convolvulaceae and Solanaceae) resistance cases have not been reported to date in Brazil.

Author details

André Andres[1], Germani Concenço[1]*, Fábio Schreiber[2], Dirceu Agostinetto[2], Leandro Vargas[3], João Behenck[2], Giovanni Antoniaci Caputo[2] and Ygor Sulzbach Alves[2]

*Address all correspondence to: germani.concenco@embrapa.br

1 Embrapa Temperate Agriculture, Pelotas, RS, Brazil

2 Federal University of Pelotas, RS, Brazil

3 Embrapa Wheat, Passo Fundo, RS, Brazil

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