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**Running Title:** Herbicide Use In South America

# **Title: HERBICIDE USE HISTORY AND PERSPECTIVE IN SOUTH AMERICA**

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**Highlights** (three major highlights, 110 characters each, including spaces)

- No-tillage, glyphosate resistant crops, and herbicide resistance were drivers of herbicide use in South America.

- Glyphosate use in proportion to other herbicides is decreasing but still is the most used herbicide.

- The characteristics of South America agriculture enforce the necessity of integrated weed control for environmental sustainability.

**Abstract: (**Maximum of 250 words)

**Background:** Agriculture on South America had a great expansion in the last decades and weed control changed according with region and crop practices.

**Objective:** The objective of this review is to present the history of herbicide use and discuss the main changes in weed management in South America.

**Methods:** Herbicide use quantities were obtained from official institution and commercial organizations in Argentina, Brazil, Chile, Paraguay and Uruguay. Data was summarized per active ingredient, herbicide mode of action or crop used. The evolution of cultivated area of the main crops in in each country and of the crop and weed management was considered to discuss the importance and the consequences of the main herbicides used.

**Results:** In Brazil in 2019 the most used herbicides were glyphosate, 2,4-D, atrazine, paraquat and diuron with 62, 15, 7, 5 and 2% in relation to the total amount used. In Argentina the rate of increasing of herbicide resistant populations is 4 cases/year, that resulted in utilization of older chemistries. Weed control in Uruguay was beneficed of pasture rotation but recently is also facing problems of continuous cropping systems. Agriculture in Chile is more diverse, but similar patterns and problems of herbicide use is present.

**Conclusions:** Intensification of agriculture**,** no-tillage, glyphosate resistant crops, and herbicide resistant weeds were the most important drivers of herbicide use changes in South America. Integrated weed management is required to provide sustainable increasing of food production in South America.

**Keywords:** evolution of agriculture, glyphosate, herbicide resistance, land use, no-tillage, 2,4-D,

**Graphical Abstract:**

**Conflict of Interest**

The authors have no conflict of interest to declare regarding the research.

**1. Introduction**

Agriculture has had great expansion around the world in the past century resulting in great changes in people's quality of life. In the past 20 years, crop and livestock production in the world increased 55 and 51%, respectively (FAO, 2021). In South America, in the same period the increase was 97% for crop and 76% for livestock production. Fifty percent of agricultural production growth in South America during 1969 to 2009 was due to increased efficiency of production factors (Trindade and Fulginiti, 2015). There are several challenges that limit the progress of agriculture in South America, including the technological variability resulting from the social and economic conditions of the several countries and the preservation of the environment. For example, a study evaluating the operational and environmental performance of Latin America and the Caribbean countries found that six countries have complete efficiency, in three the efficiency is intermediate and nine countries have efficiency limitations (Moreno-Moreno et al., 2018). These results showed that some countries have developed agriculture and meet strict work and environmental preservation policies, and that there are still needs associated with these factors to be improved in other countries. South America, due to the great availability of land, has a great capacity to increase the food production that will be necessary to meet the growth of the world population in the coming years. It should be noted that this growth is not associated with deforestation, but rather the increase in productivity of already cultivated areas and the regeneration of degraded areas, mainly pastures.

The use of herbicides to weed control has been and will be an important factor for increasing agricultural production (Kudsk and Streibig, 2003). Specific reviews related with South America countries are available about the analysis of the impacts of herbicide resistant crops (Vila-Aiub et al, 2008; Cerdeira et al., 2011; Carneiro et al., 2017; Merotto et al., 2016; Ulguim et al., 2021), regulation and public perception of herbicides (Camargo et al., 2020), crop and weed management (Oliveira et al., 2021), and analysis of herbicide risk assessment (Carbonari and Velini, 2021). However, there is no information on herbicide use history related to main changes in agriculture and weed control practices. The objective of this review is to present the history of herbicide use, discuss the main changes in weed management, and point out perspectives and needs for increasing the sustainability of weed control in the main food producing countries in South America.

**2. Herbicide use in Brazil**

**2.1 Changes in the main grain crops and use of herbicides until 2000**

Large expansion of agriculture in Brazil occurred in the early 1970s associated with migration of farmers from Southern Brazil to the unexplored areas in the Cerrado (Brazilian savanna). At that time, conventional tillage for soil and weed management was a common practice. The development of no-tillage started in the early 1970s, and one of the main difficulties was the control of perennial weeds (Almeida, 1981). After an exciting start, in the mid-1970s, no-till experienced a setback due to weed control related problems. In 1978, paraquat and diquat were the most used herbicides, and most of the farmers who did not adopt or who abandoned no-tillage attributed the fact to the high cost, the inefficiency of the herbicides, and the difficulties with the management of weeds (Gazziero et al., 2009)

At the beginning of the 1980s, no-tillage system again awakened the interest of farmers, due to the improvement of planters, benefits in soil conservation, fuel and time savings for crop implantation, availability of cover crop species, and mainly due to the greater availability of herbicides for burndown such as glyphosate and 2,4-D. In general, one application of glyphosate plus 2,4-D resulted in high efficacy to manage weed cohorts prior to planting. At that time, 2,4-D ester was the most common formulation, especially in colder regions; however, the ester formulation was withdrawn from the market in the late 1990s. Herbicide use increased dramatically with the expansion of soybean grain production. Metribuzin and linuron were a common pre-emergent herbicide program for broadleaf weed control in soybean. Oryzalin, alachlor, metolachlor, and pendimethalin were adopted as pre-emergent herbicides for grasses. In conventional system, trifluralin was incorporated into the soil. Alachlor and metolachlor were commonly used for *Commelina benghalensis* control in no-tillage systems. In post-emergence, bentazon was recommended in areas of *Raphanus rapanistrum*, *Sida rhombifolia* and *Bidens pilosa*. Also, acifluorfen was used to control *Euphorbia heterophylla*. In the early 1980's, no more than 15 active ingredients were available for soybean weed management (Gazziero,1983).

Herbicide discovery for post-emergence grass control was a milestone for minimizing troublesome weed impact in soybean. Diclofop-methyl, alloxydim , fluazifop-butyl, sethoxydim were the first herbicides introduced. Similar trend occurred with the introduction of ALS-inhibiting herbicides in the mid-1980s. Imazaquin was well adopted by growers due to high efficacy on *E. heterophylla* and rapidly replaced trifluralin and metribuzin. However, a great revolution in weed control also occurred with the launch of chlorimuron-ethyl and imazethapyr in the mid 80's due to the possibility of applying at post-emergence and high efficiency in large weeds. The intensive use of ALS-inhibiting herbicides in pre-emergence (e.g. imazaquin) and in post-emergence (e.g., chlorimuron-ethyl and imazethapyr) resulted in the rapid evolution of *E. heterophyll*a and *B. pilosa* resistant biotypes in the early 1990s (Heap, 2021). A common strategy to minimize ALS-resistant weeds was mixing three products in post-emergence, such as chlorimuron-ethyl, imazethapyr, lactofen, bentazon, fomesafen and acifluorfen. In the late 1990's resistance to ALS-inhibiting herbicides represented a major problem for weed control in Brazil (Vidal and Merotto Jr, 1999).

**2.3 Herbicide-Resistant Crops: a new era in weed management**

Glyphosate-resistant (GR) soybean was legally approved in Brazil in 2005, but was introduced illegally via Argentina and Uruguay in 1995 and 1996, respectively. In early 2000s, the cost of weed control in soybean with the conventional selective herbicides was U$40 to 50.00 ha-1 and with glyphosate in GR soybean was U$ 10 to 16.00 ha-1 (Bianchi, 2005). The intense glyphosate use, lack of adequate crop and herbicide site of action (SOA) rotation caused weed shifts despite technical guidelines and warnings for the proper use of glyphosate (Embrapa 2005, Vidal and Merotto Jr, 1999; Gazziero 2012). After that, a continuous evolution of GR weeds and weed control costs are occurring. An increase of 57, 129 and 500% in the cost of herbicides was estimated due to the occurrence of resistant *Lolium multiflorum, L. multiflorum* and *Conyza* spp., and *Digitaria insularis and Conyza* spp., respectively (Vargas et al., 2016). The use of glyphosate impacted not only the price and utilization of soybean herbicides but also the use of herbicides in other crops. The discussion below is based on existing data and will highlight the main changes directed related with GR soybean, crops associated with glyphosate used in no-tillage, and other crops where herbicides are predominantly used in Brazil.

The historical records on the use of herbicide and other pesticides in Brazil is limited before and even during the transition from the use of selective herbicides to GR soybean. The oldest information obtained started in 1980 with sales data grouped by pesticide class (Figure 1a). It is observed that until 1985 the cost spent with herbicides was nearly US$ 7 ha-1. In early 2000 when the utilization of GR soybean expanded, the cost associated with herbicides for all crops was close to US$ 27 ha-1, and increased continuously reaching US$ 45 ha-1 in 2019. The herbicide and pesticide quantity (kg ha-1) have been available since 1990 and 2000, respectively (Figure 1b). The use of herbicides in kg ha-1 increased linearly from 1990 to 2010, and has been stable after, which is close to the period related with the consolidation of GR technology use.

Information on pesticide use per active ingredient has been made available only in the past decade (IBAMA, 2021). However, until 2019 the information on pesticide use was only available for products commercialized under at least three distinct trademarks in order to protect information of original products. The analysis is presented relative (%) to the amount of herbicide used in 2009 or to the first year of available data (Figure 2). Most herbicides showed an increase of use similar to the total sum shown in Figure 1. Few herbicides varied within the period. For example, imazaquin increased from 2011 to 2015, but decreased from 2015 onwards. This variation may be associated with the increasing use of other pre- and post-emergence herbicides. Although GR-soybean was consolidated in Brazil, glyphosate showed an increase of 75% in this period (Figure 2). This increase of glyphosate use is higher than the area increase of soybean, cereal and other crops, which were 57, 39, and 31%, respectively (CONAB, 2021), which suggest an increase in the glyphosate rate.

The herbicide picloram showed an increase of 470% (Figure 2) that is likely associated with increased weed management in degraded pasture areas. Chlorimuron-ethyl showed a peak use in 2015, which is possible due to GR *Conyza* spp. management (Santos et al., 2014). However, the occurrence of ALS-resistant weeds resulted in a decrease in chlorimuron-ethyl use. The 400% growth in 2,4-D use from 2009 to 2017 (Figure 2) is likely due to the use of auxin herbicides for GR- and ALS-resistant *Conyza* spp. management. Subsequently, the use of 2,4-D slightly decreased (Figure 2) likely due to resistance to 2,4-D (Queiroz et al., 2020), as well as due to the problems related to 2,4-D off target movement in some regions of Brazil. The herbicides metsulfuron-methyl and paraquat experienced a growth of nearly 600% in the past decade, which is also related to the use as alternative herbicides to control GR-weeds. The use of clethodim grew 2300%, which was the highest among all the herbicides evaluated, and is related to the occurrence of GR-*Lolium multiflorum*, GR-*Digitaria insularis* and GR-*Eleusine indica* (Pagnoncelli et al., 2021; Leal et al., 2021, Heap, 2021).

Another source of data is a market research performed in agricultural properties from 2014 to 2019 in Brazil grouped by herbicide SOA in 18 crops (Spark, 2021). The herbicide glyphosate, inhibitor of the enolpyruvylshikimate phosphate synthase ( EPSPs) has always been the top SOA used; however, the proportion of glyphosate among other herbicides reduced from 40.8% in 2014/15 to 35.7% in the 2019/20 growing season (Figure 3). The photosystem II (FSII)-inhibiting herbicides shifted from second to third in 2015/16 likely due to reduced atrazine application in corn resulting from the increasing use of GR hybrids in this crop. Similar trend was also observed in 4-Hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Figure 3). Auxinic herbicides is currently placed second in herbicide use in Brazil. The use of auxin herbicides increased mostly for burndown in no-till areas. ALS-inhibiting herbicides showed a decrease in use likely due to the occurrence of weed resistance. On the other hand, ACCase-inhibiting herbicides grew nearly 200%, changing the ranking of this SOA from the seventh to the fourth position in the period evaluated. Glutamine synthetase (e.g. glufosinate) doubled the treated area likely related to the reduction of cost due to the recent availability of generic products and the recent ban of paraquat in Brazil.

**2.4 Current use of herbicides in Brazil**

The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) disclosed in 2019 the information about all herbicide sales regardless of the number of market products of a certain ingredient active in total amount (tons) (Table 1). The analysis of this raw data is confusing because field rates varied among the several herbicides. Therefore, we performed a treated area prediction based on the total ingredient active amount used in 2019 and on the reference dose estimated by the average label dose and in the usual field dose. The top five herbicides used in 2019 were glyphosate, 2,4-D, atrazine, paraquat and diuron with 62, 15, 7, 5 and 2% in relation to the total amount used. In relation to the estimated treated area the top five herbicides were glyphosate, 2,4-D, clethodim, paraquat and metsulfuron-methyl been used in approximately 151, 43, 41, 32 and 22 million ha (Table 1).

The commercialized quantity of glyphosate was 217,592 ton in 2019 (Table 1). The used dose of this herbicide is variable, but nowadays it can be considered as 1440 g ha-1, which results in an estimated treated area of ​​151 million ha (Table 1). Glyphosate is mostly used for burndown in soybean, corn, beans, wheat, cotton, and irrigated rice, and on layby application in coffee, orchard and planted forests. The combined area of these crops is 68.4 million ha in 2019 (CONAB, 2021). Glyphosate is also used at post-emergence in GR-soybean and corn crops, which are grown at 35.4 and 17.7 million ha, respectively. Therefore, the total area treated with glyphosate in burndown, layby and post-emergence is 121.3 million ha. The comparison of this cultivated area with the 151 million ha area obtained based on the commercialized sales indicates that approximately 30 million ha receive an extra application of glyphosate. This application may be related with a second application at post-emergence in GR crops or at layby in perennial crops. The aforementioned discussed data indicated that most GR-soybeans are using three glyphosate applications. A farm survey indicated that the average number of post-applied glyphosate increased from 1.8 in 2005/6 (official launch of GR-soybean) to 2.4 applications in the 2010/11 growing season (Adegas et al., 2012).

Paraquat was banned in Brazil in 2019, and in its last year of utilization was used on 32.7 million ha (Table 1). This highlights the paraquat importance for weed management (e.g., burndown), and the need for replacement by other herbicides. Products that might replace paraquat as a burndown option are metsulfuron-methyl, which was estimated in 22.5 million ha, followed by chlorimuron-ethyl (10.5 million ha), saflufenacil (5.5 million), glufosinate (3 million) and diquat (2,7). The 2,4-D herbicide has an estimated use of 43 million ha (Table 1), mainly in the pre-planting burndown of summer crops and in pastures.

The corn area in Brazil is approximately 18 million ha (CONAB, 2021). Herbicide diversity has decreased in corn due to the increasing GR-corn planting area. For example, nicosulfuron, a commonly applied post-emergence herbicide in corn, was used only in 1.5 million ha in 2019. In addition, mesotrione and tembotrione were used at 3.9 and 1.9 million ha, respectively (Table 1). Atrazine, a corn and sugarcane herbicide, was applied to 9.3 million ha. These informations demonstrated that there is also a predominant use of glyphosate and low use of other herbicides in corn.

The treated area with pre-emergence herbicides most used in no-tillage such as diclosulam, flumioxazin, imazethapyr, metribuzin, *S*-metolachlor, and sulfentrazone was 38,5 million ha. The total area of row crops where these herbicides are potentially used in 2019 was 73.8 million ha (CONAB, 2021). This information indicated that the estimated use of pre-emergent herbicides is nearly 50% (38.5 million ha of pre-emergent herbicides estimated used related to 73.8 million ha cultivated area). The use of these herbicides in other crops, at post-emergence or different field rates in relation to those considered in Table 1 may jeopardize these estimates. Nonetheless, our estimates corroborate to Oliveira et al. 2018, which reported 47% use in pre-emergence herbicides average across 13 crops in Brazil.

Data about herbicide use per crop is available for the seasons 2017/18 to 2019/2020 based on a market research performed in agricultural properties (Spark, 2021) (Figura 4). In soybean, total herbicides estimated treated area in this period increased from 154.7 to 170,5 ha (10%) and the cultivated area from to 35.1 to 37.0 (5%). The large increase occurred ACCase-inhibitors (28%) and synthetic auxins (23%); EPSPs increase 6%, and ALS-inhibitors decrease 13%. In corn xxxxxxxccxDiscussão dos dados da Figure 4 (em correção MAXWELL= vc lembra o que era a correção aqui indicada)

**3. Herbicide Use in Argentina**

**3.1. Historic and Use Before Transgenic Crops Resistant to Herbicides (1950-1995)**

Since the discovery and development of herbicides during the 1940s, the use of these products increased year after year. Selective herbicide application began in the late 1940s, when 2.4 D was applied mainly on corn crops. The use of this herbicide was expanded rapidly in cereal crops, from 30,000 hectares treated in 1950 to about 5,000,000 hectares treated at the end of the 1970s, mainly in corn and wheat crops. Subsequently, other auxinic herbicides such as dicamba and picloram began to be applied in mixtures with 2,4 D or MCPA. In addition, the use of herbicides was diversified in other crops such as sugar cane. At the end of seventies, herbicides were applied to more than 50% of the harvested wheat hectares, while in soybeans and corn this ratio exceeded 90% (Mársico 1980) (Table 2). In wheat, the most used herbicides for the control of broadleaf weeds were those belonging to the auxin herbicides, 2,4-D, MCPA, dicamba, and picloram. On the other hand, grass species (*Avena fatua and Lolium sp*) were controlled with ACCase inhibitor herbicide (diclofop methyl) and to a lesser extent with difenzoquat, herbicide with an unknown site of action that had been out from the market for many years. In corn, chemical control was carried out with the use of pre-sowing / pre-emergence herbicides such as atrazine, alachlor, EPTC and butylate, and at post-emergence with 2,4-D, dicamba and picloram. In soybean, the most common program was the application at pre-sowing of trifluralin, metribuzin and alachlor at pre-emergence, and acifluorfen sodium and bentazon at post emergence for the control of broadleaf weeds. Pirifenop was also applied at post-emergence for the control of grass weeds, particularly perennial such as *Sorghum halepense*. During these years chemical control was complemented with mechanical control not only during the crop season but also at fallow. Mechanical control was mostly used until the nineties

During the 1980s, many new active ingredients were introduced. In terms of millions of dollars, the herbicides market increased from 6 to 95 million dollars between 1974 and 1984, which represent 19% and 53% of the total agrochemical market for each year. In the early 1980s, new herbicides with different SOA were introduced, which were quickly adopted by farmers. One example is the use of ALS inhibitors such as metsulfuron methyl in wheat and barley. This herbicide brought relevant advantages for weed management in these crops since it can be applied in a greater window of the crop development than auxin herbicides. In addition, the spectrum of weeds was expanded to other species not satisfactorily controlled by auxinics such as *Lamium amplexicaule, Viola arvensis, Veronica arvensis, Matricaria chamomilla*, etc. The significant adoption of metsulfuron methyl is showed in the evolution of the treated area with this herbicide between 1989 and 1994, which increased from 3% to 30% of the area sown with wheat (118,000 hectares and 1,470,000) (Basile et al. 1995). Total wheat planted was 4.750.000 has and 5,147,000 has in 1989 and 1994, respectively (MAGyP, 2021). Likewise, another important advance in this crop during the eighties was the introduction of ACCase inhibitor herbicides selective to wheat such as fenoxaprop-p-ethyl plus safener for control of *Avena fatua* and clodinafop-propargil plus safener for control of *Avena fatua and Lolium sp*., that are between the most important weeds in winter cereals.

In soybean ALS inhibitor herbicides, such as chlorimuron (sulfonylureas) and imidazolinones (imazaquin, imazetapyr) as well as PPO inhibitors herbicides such as fomesafen, fluoroglycofen, and lactofen were introduced to control broadleaf weeds. In addition, ACCase inhibitors “graminicides” (fluazifop butyl, haloxyfop methyl, quizalofop ethyl, sethoxydim and cletodim) were also introduced (Table 3). The application of the new "graminicides" represented a significant advance for the control of hard-perennial grass weeds such as *Sorghum halepense and Cynodon dactylon.* Interestingly, these herbicides were also adopted to apply in sunflower crops. Likewise, in this crop, herbicides with a new SOA such as aclonifen, diflufenicam and flurochloridone were also introduced to control broadleaf weeds.

In corn, the use of pre-planting and pre-emergence herbicides was mainly represented by atrazine for the control of broadleaf weeds and alachlor, metolachlor, acetochlor for annual grasses. In addition, herbicides from the thiocarbamates family (EPTC, Butylate) applied pre-sowing and incorporated by tillage were used to control perennial grass species such as *Sorghum halepense and Cynodon dactylon*. At the late eighties’ herbicides of the group of sulfonylureas (nicosulfuron, primisulfuron) were introduced for use post-emergent for control of both annual and perennial grass species.

**3.2. *The adoption of direct sowing and incorporation of transgenic herbicide resistant varieties* (1990-2020)**

During the 1990s, there was a massive expansion of no-tillage system from 60,000 hectares, mainly in soybean crops, at the end of the 90s to 33,000,000 hectares in 2018/19, representing approximately 90% of the total cropped area (AAPRESID, 2021). Likewise, in 1996, genetic modified crops resistant to glyphosate (RR soybean, corn, and cotton) were introduced in the market. The adoption of RR soybean was higher than other crops, reaching almost 100% of the area planted with transgenic crops in eight years. Nowadays, it is almost 100% of soybean and cotton and 98% of corn (Argenbio, 2021). However, during the 90s, others herbicides were also introduced to the market such as the PPO inhibitors flumioxazin for application in soybean, corn, sorghum, sunflower and wheat, and sulfentrazone for its application in soybeans, sunflower and peanut. Likewise, ALS inhibitors belonging to the triazolpyrimidine chemical family such as flumetsulam, diclosulam and chloransulam were introduced for the control of broadleaf weeds and some grass weeds, mainly in soybean crops. In addition to the incorporation of glyphosate resistant genotypes, Glufosinate ammonium tolerant maize and Imidazolinone herbicide tolerant (BASF Clearfield crops) were introduced. IMI tolerant maize (imazapic), sunflower (imazapyr), and rice (imazapic+imazapyr) were introduced in 1998, 2003 and 2004, respectively. After that, CL plus sunflower with tolerance to imazapir and imazamox was incorporated in 2010.

The adoption of RR crops and direct seeding resulted in a significant increase in soybean area and the use of herbicides, incorporating a new practice such as chemical fallow and therefore the predominant adoption of the herbicide glyphosate. In 1994, the total agrochemical market was approximately $ 500 million (Basile et al. 1995). In 2007, this total was 1.6 billion dollars, while in 2016 it reached 2.5 billion dollars. The herbicides represent around 70% of the total market (CASAFE, personal communication). Beyond the operative and economic advantages of the RR technology, ten years after its introduction the first populations resistant to glyphosate was identified. The first case was *Sorghum halepense* from the northwest of Argentina, reported by Delucchi (Heap 2005) and identified by Vila Aiub et al (2007). From that moment the rate of increase of resistant populations was 4 cases/year, totaling 40 of which 27 have resistance to glyphosate. This was reflected in the relative increase in selective herbicides in market from 2013 to 2016 (Figure 1) particularly related to ACCase and PPO inhibitors (Ferrari, com. Personal).

**4. Herbicide Use in Uruguai**

**4.1. History of herbicide use in Uruguayan Agriculture until the twenty-first century**

Agriculture has been a major driver to the economy throughout Uruguayan history and since 1890 has undergone important technological changes in the way it has been practiced in the country (Martínez-Galarraga et al, 2019). Some of those changes are tightly related to the use of herbicides (Ernst and Siri-Prieto, 2011). The volume of herbicides historically and yearly used in the country is largely explained by the use of these products in extensive agriculture. Therefore, evolution of herbicide imports and utilization in the country is analyzed in this work related to this activity. Agriculture in Uruguay, particularly wheat cultivation, boomed by the middle of last century. At that time, land preparation and weed control relied heavily on tillage and continuous agriculture was a common practice. Soil erosion, the rapid decay in natural fertility under prolonged cultivation and weed interference were the main concerns (Bonjour, 1935). In 1911 the central commission of agricultural defense was created to regulate the control of animal pests and weeds (Uruguay, 1911). However, until 1950 weeding was still a difficult and expensive task based on tillage, manual labor and in rarely occasions on the application of inorganic compounds such as iron sulphate. In 1947 for the first time a product containing 2-metil-4-clorophenoxiacetic acid was tested in the country (Bonjour, 1949). That was the starting point in a new era of weed management. Available herbicide registration records in the country began in 1977 and imports records in 1987 (Uruguay, 2021). However, technical reports include herbicides tested and recommended between 1950 and 1977 (Bonjour, 1949; Perea and Vittori, 1975).

New or modern herbicides, as they are generally referred to, started to be developed in the late 1940s. Yet, massive adoption in Uruguay began in the 1960s when the agriculture of cereals and oilseeds had a boom period, with more than 1 million ha cultivated in the Country (Ernst and Siri-Prieto, 2011). Herbicides such as 2,4-D and MCPA were the first to be commonly used for selective weed control in wheat. Beginning in 1967 other herbicides began to be evaluated as selective options to wheat, sunflower and corn crops. Some of the first research works in the country reported data on the microtubule assembly inhibitor trifluraline and PSII inhibitors such as atrazine, simazine, diuron, linuron and bromoxinyl (Uruguay, 1969).

Continuous agriculture caused an important drop on grain yields due to the degradation of soils physical and chemical properties. Between the 1970s and 1990s, a new scheme was implemented by including a pasture phase in agricultural systems as a way to restore over-farmed land. This practice improved the soil quality and reduced soil and nutrients losses. However, land preparation and weed control before sowing any pasture or crop still relied on tillage (Ernst and Siri-Prieto, 2011). Until 1986, 60 different active ingredients from 17 SOA had been registered in Uruguay. Auxins, photosystem II and VLCFA inhibitors were the most used herbicides (Uruguay, 2021), particularly auxin herbicides used in winter crops, which dominated agriculture by that time (Figure 1b). Summer crops such as corn, sunflower and sorghum were also planted on a smaller proportion, approximately one-third, of the agricultural area but two crops a year was not a viable practice because the time needed for land preparation (Figure 1a). Herbicides from the SOA photosystem II and VLCFA inhibitors and to a lesser extent trifluralin were the most used for weed control in summer crops.

From the late 1980s, ALS and ACCase inhibitors grew in importance within herbicide registration and imports and became important tools for weed management in winter crops (Gimenez and Rios, 1993). Even though agriculture rotated with a pasture phase, to improve soil health, tillage operations over the long term still signified a great concern. In consequence, farmers began to implement no-till farming in their fields in 1991 (Marchesi, 1993). Another important milestone that would contribute importantly to the next change of agriculture in the country was the approval of the first Roundup Ready (RR) soybean cultivar in 1996. However, these technologies were not massively adopted immediately, due in part to the lack of an efficacious and cost-effective herbicide. First formulation of glyphosate was registered in Uruguay in 1978 but imported volume of this herbicide was not relevant until 2000 when Monsanto's patent expired resulting in a dramatic drop in the price. Between 1998 and 2000 imported volume of herbicides remained constant but CIF value prices dropped 25% mostly explained by the change in glyphosate price (Figure 1b).

The first 50 years (1950 – 2000) of herbicide use in Uruguay was combined with other factors that also influenced the weed population dynamics such as tillage and a rotation of grain crops with a pasture phase. Although a few weed species dominated the agricultural landscape (Plan Agropecuario, 1986) the characteristics of the agricultural production system contributed to preserve a diversified and relatively successful weed management, and up to the end of last century no cases of herbicide resistance were registered in Uruguay.

**4.2. Herbicide use in a new scenario for agriculture production**

At the beginning of the current century a series of factors converged that would impact drastically herbicide use and weed population dynamics. The drop in glyphosate price, the high soybean prices in the international market and available RR technology, already approved in the country, converged to accelerate adoption of no-till farming and to explain the shift towards RR soybeans as the main crop in the country. The agricultural system shifted in a few years from a scheme that tilled agricultural land and rotated crops with pastures where wheat was the main crop to another scheme of no-till continuous agriculture with RR soybean as the most important crop (Figure 5a). Fuel and time savings in this new scheme not only reduced production costs but also enabled double cropping (Figure 5a), and glyphosate quickly became by far the most imported and used herbicide in the country (Figure 5c).

Agriculture production and area grew importantly between 2000 and 2014 when RR soybean crop reached 1.35 million ha (DIEA, 2015). Concomitantly, herbicide use and imports boomed during this period (Figures 5a and 5c). No tillage and RR technology contributed to drastically change weed management approaches. Initially, weed management based on RR technology became a simple and economic task. Glyphosate imports escalated from representing 38% of total herbicide imports in 1999 to representing almost 70% in 2007 (Figure 5c). By 2010 weed management in RR soybean, which represented 65% of the total agricultural area (DIEA, 2015), was based almost exclusively on glyphosate and occasionally an ALS inhibitor. As a result, changes in weed species frequencies became evident (Rios et al, 2005). Around 2009 those changes were followed by concerns of farmers who argued that annual ryegrass was no longer controlled by previous rates of glyphosate and thus herbicide rates started to be increased.

Currently, herbicide resistant (HR) weeds are one of the most important problems in Uruguayan agriculture. Glyphosate resistance have been confirmed in populations of annual ryegrass (Félix and Urioste, 2016), fleabanes (*Conyza sumatrensis* and *C. bonariensis*) (unpublished data), and palmer amaranth (Gaines et al., 2021). Due in most part to this problem herbicide use have changed in recent years. Glyphosate represented 61% of CIF value imports in 2014 and 39% in 2020. Additionally, a diversification in the herbicides modes of action used in the country´s agriculture production is noted and reflected in herbicide imports (Figure 6c).

**5. Herbicide Use in Chile**

The use of herbicides in Chile has a very dynamic history, which has been associated with the development of the agricultural and forestry sector. Although there is limited availability of information on this specific evolution, there are some official records that allow us to analyze these changes throughout time. An interesting fact that is worth to highlight, due to its impact on the demand for pesticides, is the political period know as “agrarian reform” carried out in Chile and that took place between 1963 and 1973. During this period the Chilean government assumed an important role in the development and generation of technological packages with an intensive use of pesticides (Glico, 2021).

**5.1. The herbicide market between the years 1960 to 1990**

The IV agricultural Chilean census (1964-1965) shows that in the 1960s Chile had a total of 3.2 million hectares sown or planted, among which almost 40% corresponded to forage species, 35% to cereals and farms, 13% to forestry, 3.6% to industrial crops, 3.4% to vineyards, 2.7% to vegetables and flowers and 2.5% to fruit trees (Statistics and Census Directorate, 1969). The data collected indicated that between the years 1958-1963 a total of 361.2 tons of herbicide formulations were imported, corresponding to 48 names of different products, which are mostly systemic herbicides derived or from combinations of 2,4D and MCPA. Its use was widespread mainly for viticulture, fruit trees, corn and beets, but it was limited in horticulture, rice fields and wheat. In those years, problems such as the lack of legislation regulating the price of herbicides, the reduced availability of application equipment due to its high cost and the lack of knowledge by farmers of the importance of weed control in crops, limited the dissemination of its use in the country (CEPAL, 1966). Lazen (1970) describes for this decade the use of dalapon and aminotriazole in fruit orchards to control *Cynodon dactylon, Paspalum sp* and *Sorghum halepense*. Later, and with the introduction of paraquat, began a more extensive use of herbicides, but always limiting them to drench applications to fruit trees, seeking to replace manual labor. Between 1965-1968, the first research studies with soil-active herbicides were conducted, mainly based on triazines, ureas, uracils and benzonitriles.

From the mid-1970s to the late 1990s, the national market for pesticides grew more than 15 times (Ormeño, 1999), reaching a value of over 44 million dollars in 1990, when herbicides reached a value of almost 19 million dollars, equivalent to 42% of imported pesticides (ODEPA, 2021). This rise in the herbicide market value was due to the development and modernization of agriculture, which led to an increase in the planted area, intensive use of labor, and also an increase in the use of herbicides to rise yields and a decrease in the dependence on labor in weed control (Kogan, 1992).

**5.2. The Chilean herbicide market today**

Records of agrochemical imports since the 90s show a sustained increase in the consumption of herbicides, over fungicides and insecticides, especially between the years 1990-2015, where herbicides corresponded to 45% of imported pesticides. From 2015 to the present, herbicides correspond to 38% of agrochemical imports, followed by insecticides with 33% and fungicides with 28% (Figure 6a). In a similar way, the value of the national herbicide market has continued to increase over the last 30 years, with an average increase of 6% per year, reaching today 77 million dollars (Figure 6b) (ODEPA, 2021). It is important to note that in Chile the active ingredients of pesticides are not manufactured and only in specific cases some products are formulated (Ormeño 1999). In summary almost 100% of the herbicides used in Chile are imported from other countries such as Argentina, China, USA, Germany and Brazil (ODEPA 2021). This sustained increase in the consumption of herbicides is directly related to the productive reorganization of the country that began in the mid-seventies and with the commercial opening in the eighties, which led to an increase in three times in area of fruit trees, moving from 89 thousand hectares in 1976 to 230 thousand according to the last agricultural census (2007), as well as vineyards where the planted area increased by 47 thousand hectares between 1997 to 2007. During this same period also increased planted hectares with flowers and seedlings.

According to the records of the Agricultural and Livestock Service (SAG), currently in Chile there are 127 different active ingredients of herbicides and about 327 commercial names. The top sold at the country level are glyphosate, paraquat, MCPA, simazine, oxyfluorfen and pendimethalin (SAG, 2021). According to the latest data on pesticide sale pesticides for 2019, in the northern area of the country where the production is fruit and vegetable (Atacama to Coquimbo), as well as the central area (Valparaíso to Maule) where fruit and vegetable crops are produced, vineyards, industrial crops and forest plantations, the best-selling herbicides are glyphosate and paraquat, while in the southern zone (Ñuble a Los Lagos), where cereals and forest plantations are mainly concentrated, the most sold herbicides together with glyphosate and paraquat are MCPA, 2,4-D, simazine, metsulfuron, pendimethalin, trifluralin, oxyfluorphen, fluoxypyr, and S-metolachlor (SAG, 2019).

The widespread use of glyphosate and paraquat in Chile is explained by the fall in their prices, which began to be observed since the eighties, especially in herbicides such as paraquat, and also MCPA, which had a low price at the end of the 1980s. The other important drop in prices was that of glyphosate due to the expiration of its patent (1974-2000), which led to the commercialization of a greater number of distributors as all generic products (Ormeño 1999). With the increasingly widespread use of herbicides, the first cases of herbicide-resistant weeds began to be seen in the early 1990s. To date, resistance to Acetyl CoA inhibitor herbicides such as haloxyfop-methyl has been described in species such as *Lolium perenne* (2001), *Lolium multiflorum* (1998), *Lolium rigium* (1997), Avena fatua (1998), and *Cynosurus echinatus* (1999) in oat, canola and lupine crops. In 2001, resistance to glyphosate was described in *Lolium perenne* and *L. multiflorum* in vineyards and fruit trees and in 2005 to ALS inhibitors *Schoenoplectus mucronatus* and *Alisma plantago-aquatica* in rice crops, as well as in *Sorghum halepense* (2009) in corn and in *Raphanus sativus* (2010), *Anthemis cotula* (2010), *Anthemis arvensis* (2010), and *Silene gallica* (2012) in oats (HEAP, 2021).

6**. Herbicide use in Paraguay**

Agriculture in Paraguay has experienced a significant growth in the past decades. Soybean, corn and irrigated rice are the most cultivated crops. Most of the technology used in cropping systems in Paraguay are similar to Brazil and Argentina (Salas and Sarubbi 2013). The characteristics of herbicide use in Paraguay are similar to those described above for these countries. Information regarding the use of herbicides by active ingredient is available for 2018 to 2020 (OCIT, 2021). Paraquat, 2,4-D, and glyphosate are the top used herbicides (Figure 7). Glyphosate represented nearly 50% of the total herbicide use in 2018 (Figure 7). However, glyphosate use reduced 31% from 2018 to 2020, which is likely due to the evolution of GR-weeds in Paraguay. The reduction in glyphosate use in Paraguay resulted in the increase of other non-selective herbicides, including glufosinate. Moreover, there was a shift in auxin herbicide use, 2,4-D decreased 29% from 2018 to 2020, whereas triclopyr increased 253% in the same period. Nonetheless, 2,4-D use was higher than triclopyr in 2020. Similar to other countries in South America, herbicide data availability is limited in Paraguay. Public and detailed pesticide database in Paraguay will provide better monitoring of agricultural practices associated with weed, insect and disease management.

**7. Herbicide use in Other South American Countries**

Pesticide data from local official authorities of private companies for the other South America countries was not identified. Food and Agriculture Organization (FAO) statistics database (http://www.fao.org/faostat/en/#home) provides information about pesticide categories since 1990. FAO stats showed that total pesticide use in Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname and Venezuela had a peak in 2005 followed by wide variation in subsequent years (data not shown). Therefore, the available results are difficult to be analyzed because agriculture in these countries has had constant growth and the variation found is possibly related to the difficulty of obtaining local information. Agriculture in these countries is quite variable but has increased in relation to the use of technologies including the use of herbicides in a similar way to that diagnosed for the other South America countries.

**8 – Future perspective of herbicide use in South America**

The large extension of row crops mainly soybean and no-tillage had driven herbicide use in the countries with large agriculture in South America. This indicates the actual large complexity of the burndown operation in no-tillage systems based on the use of different herbicides. As indicated in the brief history of the no-tillage system, the efficacy of herbicides for managing weeds prior to crop planting was a key factor for the evolution of this system in the early 1980s. Nowadays, several weeds are resistant to herbicides used in burndown in South America (Vidal and Merotto Jr, 1999; Leal et al., 2021, Heap, 2021). This indicates that the burndown operation, which is the basis of vegetation management in no-till, poses a high risk for the evolution of weed resistance to herbicides. This operation should be considered strategically in crop management by farmers, and should be considered as a priority for research in relation to the development of complementary alternatives technologies to herbicides in order to provide continuity in the sustainability of no-till. In addition, herbicide banning decisions such as paraquat must consider the whole scenario of weed management for a better achievement of environment sustainability.

The introduction of herbicides with new SOA was worldwide interrupted at the beginning of the nineties (Westwood 2018) due to the impacts of RR crops. From the 2000 new SOA such as saflufenacil, tolpyratalato, pyroxsasulfone, mesotrione, topramezone, pinoxaden were introduced in South America, but all of them had particularities that limit its broad utilization. The introduction of new transgenic traits related to 2,4-D, dicamba, glufosinate and isoxaflutole will provide the utilization at new SOA for post emergence application. Beyond the advantages of these technologies, it is necessary to learn the lesson of glyphosate. If new technologies are used without criteria based on sustainable use, the wheel will turn, and new cases of herbicide resistant weeds will continue to occur. Therefore, the history of herbicide use discussed in this review indicates that technology even the technologies with large efficiency must be preserved to obtain a sustainable and economic use.

Besides the need to better manage weeds, public concern for the use of herbicides (and other agrochemicals) is also contributing to revisit the principles of integrated weed management in order to decrease reliance on herbicides and thus selection pressure on weed communities. Weed management should focus on the integration of new and old technologies with the main objective of diversifying the strategies of control. Research in service crops management, roller crimpers, site specific weed management using drone images and smart sprayers, and GM crops with herbicide tolerant stacked traits must be used together (Garcia et al., 2021). Production and society signals seem to converge in the need to use herbicides in a more judiciously way. However, the need to feed an increasing world population makes it difficult to project food and fiber productions without herbicides in the near future.

As we rapidly face the impact of climate change, our practices on weed management must be reviewed and validated, once again, to ensure their sustainability from an environmental, social and economic point of view. This “new view” requires to keep in mind the importance of weed impact on food production systems (“weed interference”) as well as select more effective and ecofriendly alternatives for weed management. Weed management alternatives are currently being challenge to incorporate technology-based decision tools using environmental data series to adjust weed emergence models with the aim to optimize herbicide spraying and to reduce the use and dependence on chemical weed alternatives. Intensity of weed control in different agroecosystems also needs to be updated, since the increasing demand for more biodiverse landscapes. In this analysis, a future “glyphosate banned” scenario should also be considered, since collective sues are challenging court decisions. This scenario will probably mean an increase use of other herbicides, such as contact and soil active products, since labor availability in worldwide agriculture seems to have a low projection.

**9 - Conclusions**

Several changes occurred in the South America agriculture in the last decades. Intensification of agriculture**,** no-tillage, glyphosate resistant crops, and herbicide resistant weeds were the most important drivers of herbicide use changes in South America. Glyphosate is the herbicide most used across all different agriculture systems and weed resistance to this herbicide is a challenge to the current weed control practices. Since no new broadly used SOA had been available the use of older herbicides is occurring applied in different moments or associated with transgenic traits.

In the modern agriculture, weed control is one of the center pieces of evolution and development of new technologies. New technologies such as sensors, autonomous machines, and molecular RNAi could revolutionize weed control in the future. However, currently and in the next decades food production will be continuous dependent on the weed control based on herbicides. In South America there still a large diversity of technology use and the implementation of integrated weed management is required to provide sustainable increasing of food production.

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Table 1 – Herbicide sales (ton), reference dose, e estimated treated area for all herbices commercialized in Brazil in 2019 no Brasil. Fonte: Ibama (2021).

|  |  |  |  |
| --- | --- | --- | --- |
| **Active Ingredient** | **Sales** | **Reference dose** | **Estimated treated** |
|  | **(ton ia)** | **(g/ha ia)** | **area (1000 ha)** |
| 2,4-D | 52426,9 | 1209 | 43363,9 |
| ametrina | 4175,5 | 3250 | 1284,8 |
| amicarbazona | 2122,6 | 1400 | 1516,1 |
| aminopiralide | 407,7 | 110 | 3706,5 |
| atrazina | 23429,4 | 2500 | 9371,0 |
| bentazona | 1294,5 | 720 | 1798,0 |
| bispiribaque-sódico | 3,7 | 50 | 74,6 |
| carfentrazona-etílica | 132,7 | 35 | 3790,2 |
| cialofope-butílico | 78,7 | 450 | 174,9 |
| cletodim | 5854,1 | 144 | 40653,6 |
| clodinafope-Propargil | 34,2 | 60 | 570,4 |
| clomazona | 5598,2 | 1000 | 5598,2 |
| cloransulam-metílico | 32,7 | 35 | 933,2 |
| clorimurom-etílico | 316,7 | 30 | 10556,5 |
| dibrometo de diquate | 1374,6 | 500 | 2749,3 |
| dicamba | 43,4 | 480 | 90,4 |
| dicloreto de paraquate | 16398,1 | 500 | 32796,3 |
| diclosulam | 149,4 | 30 | 4980,3 |
| diurom | 8001,1 | 2500 | 3200,4 |
| etoxissulfurom | 9,7 | 120 | 80,5 |
| fenoxaprope-etílico | 11,1 | 100 | 110,6 |
| fenoxaprope-P-etílico | 128,7 | 100 | 1287,2 |
| florpirauxifem-benzílico | 2,8 | 30 | 93,7 |
| fluazifope-p-butílico | 113,3 | 250 | 453,1 |
| fluazifop-P-butílico | 8,0 | 250 | 31,9 |
| flumetsulam | 10,0 | 120 | 83,1 |
| flumicloraque-pentílico | 33,4 | 60 | 557,5 |
| flumioxazina | 787,2 | 50 | 15744,6 |
| fluroxipir-meptílico | 418,8 | 576 | 727,1 |
| fomesafem | 348,9 | 250 | 1395,5 |
| glifosato | 217592,2 | 1440 | 151105,7 |
| glufosinato de amônio | 1489,7 | 500 | 2979,4 |
| halossulfurom-metílico | 1,2 | 112 | 11,0 |
| haloxifope-P-metílico | 934,0 | 62 | 15064,9 |
| hexazinona | 1625,0 | 1500 | 1083,4 |
| imazamoxi | 7,4 | 42 | 176,3 |
| imazapique | 91,5 | 140 | 653,7 |
| imazapir | 128,5 | 250 | 514,1 |
| imazaquim | 4,3 | 150 | 28,4 |
| imazetapir | 803,5 | 106 | 7580,2 |
| indaziflam | 74,2 | 100 | 741,7 |
| iodosulfurom-metílico | 2,0 | 5 | 405,8 |
| linurom | 54,8 | 900 | 60,9 |
| mcpa | 184,3 | 585 | 315,0 |
| mesotriona | 465,6 | 120 | 3880,4 |
| metribuzim | 846,9 | 480 | 1764,4 |
| metsulfurom-metílico | 106,6 | 4,8 | 22201,7 |
| MSMA | 1885,1 | 2880 | 654,6 |
| nicosulfurom | 65,2 | 45 | 1448,2 |
| oxadiazona | 10,8 | 1600 | 6,8 |
| oxifluorfem | 139,1 | 720 | 193,2 |
| pendimetalina | 158,8 | 1000 | 158,8 |
| penoxsulam | 12,1 | 72 | 168,2 |
| picloram | 3827,5 | 582 | 6576,4 |
| pirazossulfurom-etílico | 1,0 | 20 | 50,0 |
| piritiobaque-sódico | 20,1 | 98 | 204,7 |
| piroxsulam | 2,6 | 18 | 145,8 |
| profoxidim | 8,3 | 100 | 83,5 |
| propanil | 173,0 | 2880 | 60,1 |
| propaquizafope | 0,0 | 125 | 0,0 |
| quincloraque | 83,0 | 750 | 110,7 |
| quizalofope-p-etílico | 122,1 | 100 | 1221,1 |
| quizalofope-p-tefurílico | 42,0 | 100 | 420,4 |
| s-metolacloro | 6061,3 | 1440 | 4209,2 |
| saflufenacil | 193,7 | 35 | 5533,3 |
| setoxidim | 6,6 | 230 | 28,5 |
| simazina | 394,2 | 2000 | 197,1 |
| sulfentrazona | 1991,0 | 470 | 4236,2 |
| tembotrione | 188,4 | 100 | 1884,2 |
| triclopir-butotílico | 1926,9 | 680 | 2833,7 |
| trifloxissulfurom-sódico | 1,3 | 15 | 89,0 |
| trifluralina | 1887,4 | 1500 | 1258,3 |
| **Total** | **345395,8** |  |  |

**Table 2**. Herbicide treated and harvested area of different crops in Argentina in 1978 (Marsico 1980).

|  |  |  |
| --- | --- | --- |
| **Crops** | **Treated area (ha)** | **Harvested area (ha).\*** |
| Barley | 200.000 | 710.0000 |
| Corn | 2.500.000 | 2.660.000 |
| Cotton | 150.000 | 607.000 |
| Oat | 300.000 | 430.000 |
| Peanut | 220.000 | 428.000 |
| Rice | 20.000 | 95.000 |
| Rye | 220.000 | 240.000 |
| Soybean | 1.100.000 | 1.150.000 |
| Sugar cane | 140.000 | 343.000 |
| Sunflower | 10.000\* | 2.000.000 |
| Wheat | 2.200.000 | 3.910.000 |

\*Data from MAGyP

**Table 3**. Decade of Introduction of different herbicides and site of actions in the soybean market in Argentina

|  |  |  |
| --- | --- | --- |
| **Seventies** | **Eighties** | **Nineties** |
| Metribuzin (PS II) | Metolaclor (VLFA) | Flumetsulam (ALS) |
| Alaclor(VLFA) | Fomesafen (PPO) | Diclosulam (ALS) |
| Pirifenop (ACCase) | Fluoroglicofen (PPO) | Cloransulam (ALS) |
| Trifluralin (Microtubule assembly) | Fluazifop butyl (ACCase) | Propaquizafop (ACCase) |
| Bentazon (PSII) | Haloxifop methyl (ACCase) | Glyphosate\* (EPSPS) |
| Acifluorfen (PPO) | Quizalofop etil (ACCase) | Sufentrazone (PPO) |
|  | Setoxidim (ACCase) | Flumioxazin (PPO) |
|  | Cletodim (ACCase) |  |
|  | Imazaquin (ALS) |  |

\*In RR Soybean

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