Herbicide use history and perspective in South America

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Abstract: Background: Agriculture in South America (SA) had a great expansion in the last decades and weed control changed accordingly 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 SA.

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

Results: In 2019 the most used herbicides in Brazil were glyphosate, 2,4-D, atrazine, paraquat and diuron representing 62, 15, 7, 5 and 2% of the total amount used. In Argentina, the increasing selection of herbicide resistant populations (4 cases/year), resulted in utilization of older chemistries. Weed control in Uruguay is traditionally benefited from crop/pasture rotations but recently is also facing problems of continuous cropping systems. Agriculture in Chile is more diverse, but similar patterns and problems of herbicide use are present.

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

Keywords: Evolution of agriculture; Glyphosate; Herbicide resistance, Land use, No-tillage, 2,4-D.

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1. Introduction

Agriculture has had great expansion around the world in the past century resulting in changes in people's quality of life. In the past 20 years, crop and livestock production in the world increased 55 and 51%, respectively (Food and Agriculture Organization of United Nations, 2022). In South America (SA), in the same period the increase was 97% for crop and 76% for livestock production. Fifty percent of agricultural production growth in SA between 1969 and 2009 was due to the increased efficiency of production factors (Trindade, Fulginiti, 2015). However, there are several challenges limiting the progress of agriculture in SA, including variable access to modern technology, resulting from different social and economic conditions, and the need to increase 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 had complete efficiency, in three the efficiency was intermediate and nine countries had efficiency limitations (Moreno-Moreno *et al.*, 2018). Therefore, some countries have developed efficient agriculture and environmental preservation policies, and others still need to improve these factors. South America, due to the great availability of land, has a large potential 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 cultivated areas and the regeneration of degraded areas, including pastures.

Herbicide use for weed management has been and will be an important factor for increasing agricultural production (Kudsk, Streibig, 2003). Specific reviews are available on the analysis of the impacts of herbicide resistant crops in SA countries (Vila-Aiub *et al.*, 2008; Cerdeira *et al.*, 2011; Merotto *et al.*, 2016; Ulguim *et al.*, 2021; Garcia *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, Velini, 2021). However, there is no information on herbicide use history related to main changes in agriculture and weed management practices. The objective of this review is to present the history of herbicide use, discuss the main changes in weed management, and identify perspectives and needs for increasing sustainability of weed management 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 management related problems. In 1978, paraquat and diquat were the most used herbicides in no-till systems. Growers who did not adopt or who abandoned no-tillage attributed it to the high cost, low herbicide efficacy, and difficulty to manage troublesome weeds (Gazziero *et al.*, 2009).

At the beginning of the 1980s, no-tillage system again arouse the growers' interest due to the improvement in farm equipment (e.g., planters), benefits in soil conservation, fuel and time savings for crop establishment, high availability of cover crop species, but mainly due to the availability of burndown herbicides, 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 at Southern Brazil; however, the 2,4-D-ester formulation was withdrawn from the market in the late 1990s due to drift issues. Herbicide use increased dramatically with the expansion of soybean grain production area. Metribuzin and linuron were a common pre-emergent (PRE) herbicide options for broadleaf weed control in soybean (Gazziero, personal communication). Oryzalin, alachlor, metolachlor, and pendimethalin were adopted as PRE herbicides for grasses. In tilled systems, trifluralin was incorporated into the soil. Alachlor and metolachlor were commonly used for *Commelina benghalensis* control in no-tillage systems. In post-emergence (POST), bentazon was recommended in areas with infestations of *Raphanus raphanistrum*, *Sida rhombifolia* and *Bidens pilosa*. Also, acifluorfen was used to control *Euphorbia heterophylla*. In the early 1980, no more than 15 active ingredients were available for soybean weed management (Gazziero, 1983).

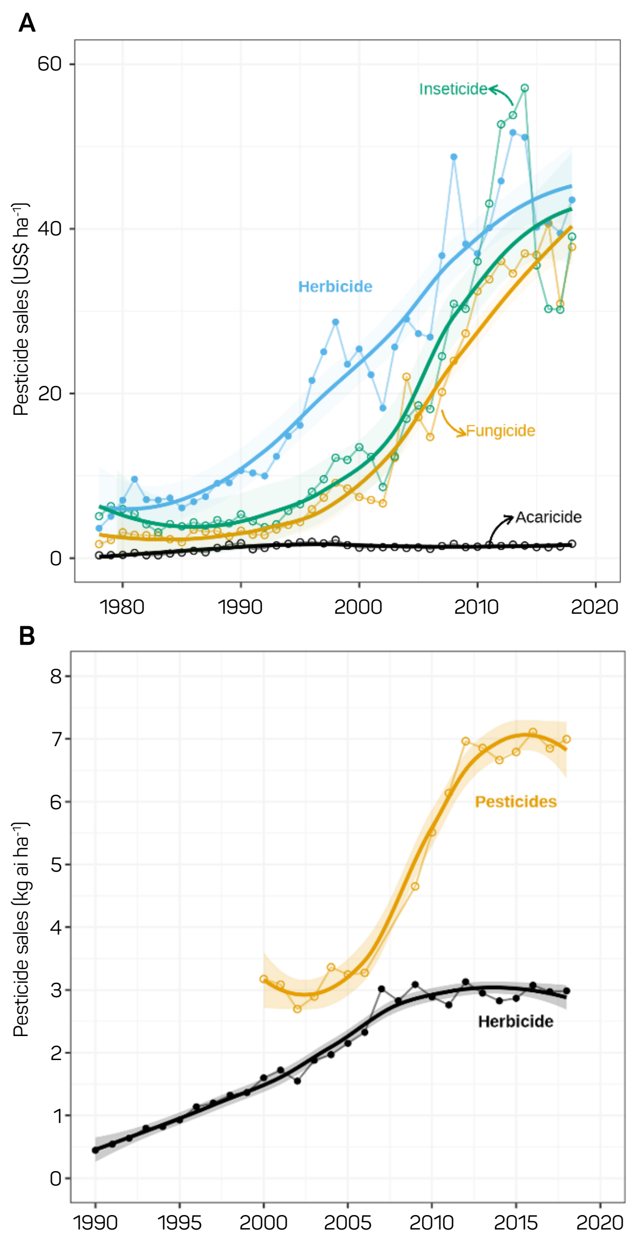
Herbicide discovery for POST grass control was a milestone for minimizing the impact of troublesome weeds in soybean. Diclofop-methyl, alloxydim , fluazifop-butyl and sethoxydim were the first herbicides introduced. A similar trend occurred with the introduction of ALS-inhibiting herbicides in the mid-1980s. For example, imazaquin was massively adopted by growers due to high efficacy on *E. heterophylla* and rapidly replaced trifluralin and metribuzin. In addition, a revolution in weed management occurred with the launching of chlorimuron-ethyl and imazethapyr in the mid 1980 due to the possibility of applying high efficacy herbicides in POST of soybean. The intensive use of ALS-inhibiting herbicides in PRE (e.g., imazaquin) and in POST (e.g., chlorimuron-ethyl and imazethapyr) resulted in the rapid selection of *E. heterophyll*a and *B. pilosa* resistant biotypes in the early 1990s (Heap, 2022). A common strategy to minimize ALS-resistant weeds was mixing three products in POST, out of options such as chlorimuron-ethyl, imazethapyr, lactofen, bentazon, fomesafen and acifluorfen. In the late 1990 resistance to ALS-inhibiting herbicides represented a major problem for weed control in Brazil (Vidal, Merotto Jr, 1999).

2.2 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 management in soybean with the conventional selective herbicides was U$40 to 50 ha^{-1} and with glyphosate in GR soybean was U$10 to 16 ha^{-1} (Bianchi, 2005). The intense glyphosate use, lack of adequate crop and herbicide site of action (SOA) rotation resulted in weed shifts despite technical guidelines and warnings for proper glyphosate use (Empresa Brasileira de Pesquisa Agropecuária, 2005; Vidal, Merotto Jr, 1999; Gazziero, 2012). Ever since, a continuous evolution of GR weeds and an increase in weed management costs occurred in Brazil. An increase of 57, 129 and 500% in the cost of herbicides has been estimated due to the occurrence of resistant *Lolium multiflorum, Conyza* spp., and *Digitaria insularis*, respectively (Vargas *et al.*, 2016). The use of glyphosate impacted not only on the price and utilization of soybean herbicides but also on herbicide use in other crops.

The historical records on herbicide use and other pesticides in Brazil is limited before and during the transition from the use of selective herbicides to GR soybean production. The oldest information obtained was from 1980 with sales data (US$ ha^{-1}) grouped by pesticide class (Figure 1A). Until 1985 the cost of 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 volume of herbicide and pesticide used (kg ha^{-1}) is available from 1990 and 2000, respectively (Figure 1B). The amount of herbicide use increased linearly from 1990 to 2010, and plateaued after this year, which is around the period where GR technology was massively adopted.

Information on pesticide use per active ingredient has been made available only in the past decade (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2020). However, until 2019 the information on pesticide use was only available for products commercialized



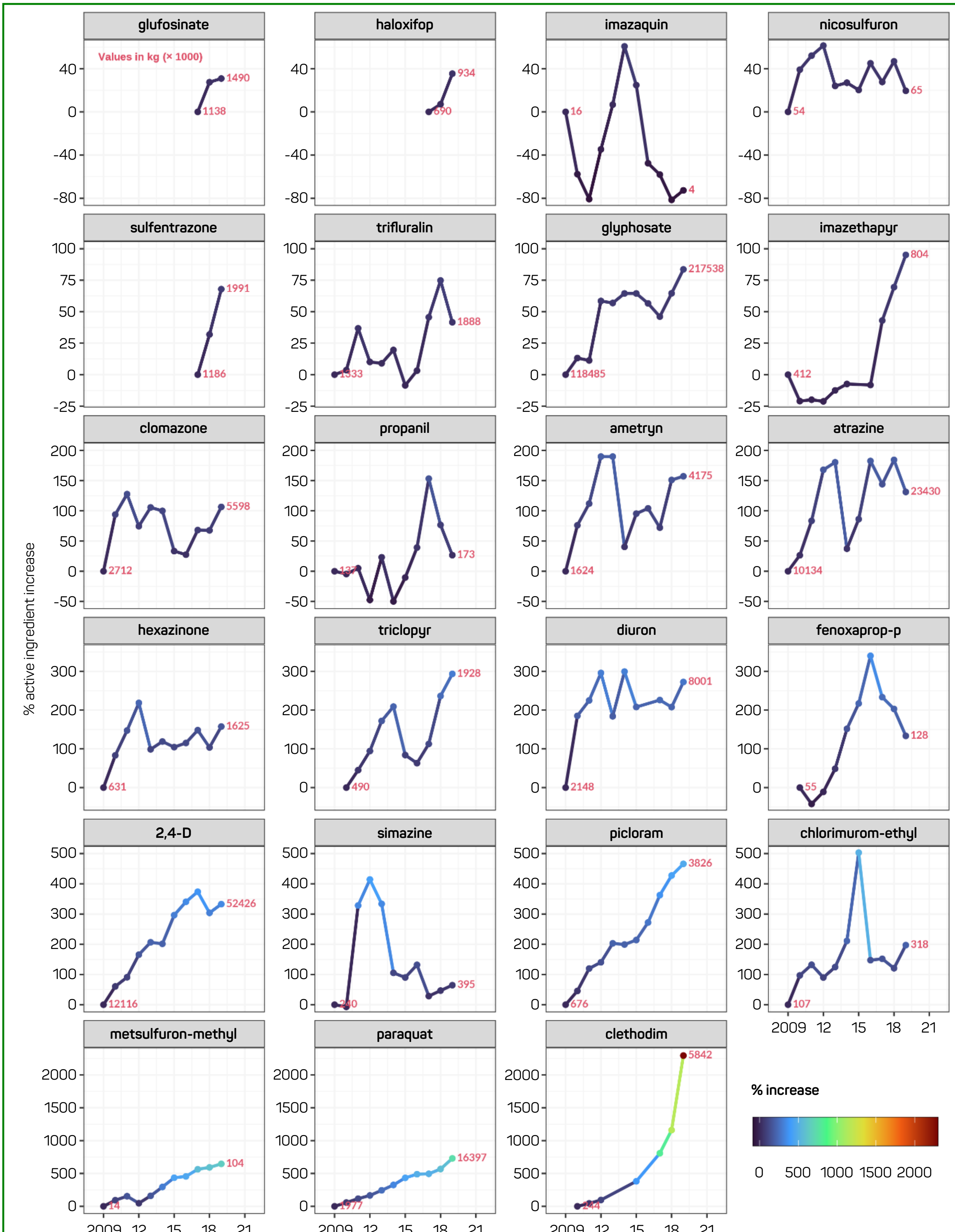
SOURCE: Adapted from IBAMA, 2020 and FAO, 2022.

Figure 1 - Estimated pesticides (herbicide, insecticide, fungicide, and acaricide) sales in US$ ha^{-1} (A) and kg ha^{-1} (B) from 1990 to 2020 in Brazil.

under at least three different trademarks in order to protect information of original products. The analysis is presented as percentage of the herbicide amount used in 2009 or to the first year of available data (Figure 2). Most herbicides showed an increase comparable to the total sum shown in Figure 1. Few herbicides varied within the period. For example, imazaquin increased from 2011 to 2014, but decreased from 2014 onwards. This variation may be associated with the increasing use of other PRE and POST herbicides. Although GR-soybean was consolidated in Brazil, glyphosate showed an increase of 75% in this period (Figure 2). This increase in glyphosate use is higher than the increase in soybean area, cereal and other crops, which were 57, 39, and 31%, respectively (Companhia Nacional de Abastecimento, 2022), which suggests an increase in glyphosate rates.

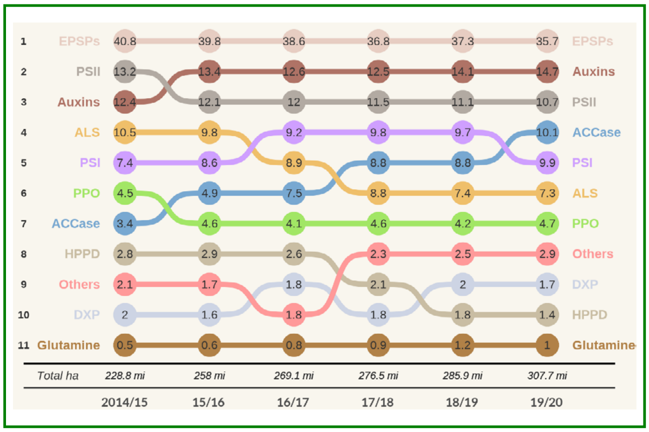
The herbicide picloram showed an increase of 470% (Figure 2) that is likely associated with an increase in weed management practices in pasture areas. Chlorimuron-ethyl showed a peak in its use in 2015, which is most probably associated to GR *Conyza* spp. management (Santos *et al.*, 2014). However, 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 increase 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, 2022). The expiration of many herbicide active ingredient patents in the early 2000s, followed by the end of the first generation of GR soybean patent in 2016 (Haggblade *et al.*, 2017) also contributed for the greater use of herbicides in Brazil, especially glyphosate. The patent loss, associate with generic formulations, tends to cause a price dropping and facilitate the access to the active ingredients.

Another source of data is a market research study 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 use relative to the 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-tillage areas. ALS-inhibiting herbicides showed a decrease in use likely due to the occurrence of herbicide 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



SOURCE: Adapted from IBAMA, 2020

Figure 2 - Percentage of herbicide active ingredient increase from 2009 to 2019 in Brazil. Values in red represents herbicide active ingredient (kg * 1000) documented in the first and last year.



SOURCE: Spark, 2021

Figure 3 - Ranking of herbicide sites of action use from 2014/15 to 2019/20 growing season in Brazil. Values in the dots represent the percentage use of each herbicide site of action by growing season.

related to the reduction of cost due to the recent availability of generic products and the recent ban of paraquat in Brazil.

2.3 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 marketed product formulations of certain active ingredients (Table 1). The data analysis is challenging due to field rates variation among the several herbicides. Therefore, we performed a treated area prediction based on the total amount of each active amount used in 2019 and a reference dose estimated by the average label dose used in usual field conditions. The top five herbicides used in 2019 were glyphosate, 2,4-D, atrazine, paraquat and diuron with 62, 15, 7, 5, and 2% relative 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, used in approximately 151, 43, 41, 32 and 22 million ha.

The commercialized amount of glyphosate was 217,592 ton in 2019 (Table 1). The dose per hectare of this herbicide is variable, but herein it is considered an average of 1440 g ha^{-1}, which results in an estimated treated area of 151 million ha. Glyphosate is mostly used for burndown in several crops, including: soybean, corn, beans, wheat, cotton and irrigated rice; and on layby applications in coffee, orchards and planted forests. The combined area of these crops was 68.4 million ha in 2019 (Companhia Nacional de Abastecimento, 2022). Glyphosate is also used at POST 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 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 in GR crops or at layby in perennial crops. These data suggest that most GR-soybeans are being sprayed three times with glyphosate during the growth cycle. A growers 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 it was used in 32.7 million ha in the last year that was allowed (Table 1). This highlights paraquat importance for weed management (e.g., burndown), and the need for replacement by other herbicides. Herbicides 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 million). The 2,4-D herbicide has an estimated use of 43 million ha (Table 1), mostly in the pre-planting burndown of summer crops and in pastures.

The corn area in Brazil is approximately 18 million ha (Companhia Nacional de Abastecimento, 2022). Herbicide diversity has decreased in corn due to the increasing GR-corn planting area. For example, nicosulfuron, a commonly POST applied 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, an herbicide used in corn and sugarcane, 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 most-used PRE herbicides in no-tillage was 38,5 million ha and included herbicides such as diclosulam, flumioxazin, imazethapyr, metribuzin, *S*-metolachlor and sulfentrazone. The total area of row crops where these herbicides are potentially used in 2019 was 73.8 million ha (Companhia Nacional de Abastecimento, 2022). This information indicated that the estimated use of PRE herbicides is nearly 50% (38.5 million ha of PRE herbicides estimated used related to 73.8 million ha of cultivated area). The use of these herbicides in other crops, at POST or different field rates in relation to those considered in Table 1 may jeopardize these estimates. Nonetheless, our estimates corroborate to Oliveira *et al.* (2021), which reported 47% use of PRE 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 the market research study performed in agricultural properties (Spark, 2021). In soybean, total herbicides estimated treated area in this period increased from 154.7 to 170.5 million ha (10%) (Figure 4) and the cultivated area from to 35.1 to 37.0 million ha (5%) (Companhia Nacional de Abastecimento, 2022). The large increase occurred in ACCase-inhibitors, 20.1 to 25.8 million ha (28%), and synthetic auxins, 12.1

Table 1 - Herbicide sales (tons of active ingredient), reference dose (g ha^{-1}) and estimated treated area (1000 ha) for all herbicides commercialized in Brazil in 2019. Source: IBAMA (2020).

Active Ingredient	Sales	Reference dose	Estimated treated area
(a.i.)	(tons a.i.)	(g ha^{-1})	(1000 ha)
2,4-D	52426.9	1209	43363.9
ametryn	4175.5	3250	1284.8
amicarbazone	2122.6	1400	1516.1
aminopyralid	407.7	110	3706.5
atrazine	23429.4	2500	9371.0
bentazon	1294.5	720	1798.0
bispyribac-sodium	3.7	50	74.6
carfentrazone-ethyl	132.7	35	3790.2
clethodim	5854.1	144	40653.6
clodinafop-Propargyl	34.2	60	570.4
clomazone	5598.2	1000	5598.2
cloransulam-methyl	32.7	35	933.2
clorimuron-ethyl	316.7	30	10556.5
cyhalofop-buthyl	78.7	450	174.9
dicamba	43.4	480	90.4
diclosulam	149.4	30	4980.3
diquat dibromid	1374.6	500	2749.3
diuron	8001.1	2500	3200.4
ethoxysulfuron	9.7	120	80.5
fenoxaprop-ethyl	11.1	100	110.6
fenoxaprop-P-ethyl	128.7	100	1287.2
florpyrauxifen-benzyl	2.8	30	93.7
fluazifop-p-butyl	113.3	250	453.1
fluazifop-P-butyl	8.0	250	31.9
flumetsulam	10.0	120	83.1
flumiclorac-pentyl	33.4	60	557.5
flumioxazin	787.2	50	15744.6
fluroxypyr-meptyl	418.8	576	727.1
fomesafen	348.9	250	1395.5
glufosinate-ammonium	1489.7	500	2979.4
glyphosate	217592.2	1440	151105.7
halosulfuron-methyl	1.2	112	11.0
haloxifop-P-methyl	934.0	62	15064.9
hexazinone	1625.0	1500	1083.4
imazamox	7.4	42	176.3
imazapic	91.5	140	653.7
imazapyr	128.5	250	514.1
imazaquin	4.3	150	28.4
imazethapyr	803.5	106	7580.2
indaziflam	74.2	100	741.7

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Continuation

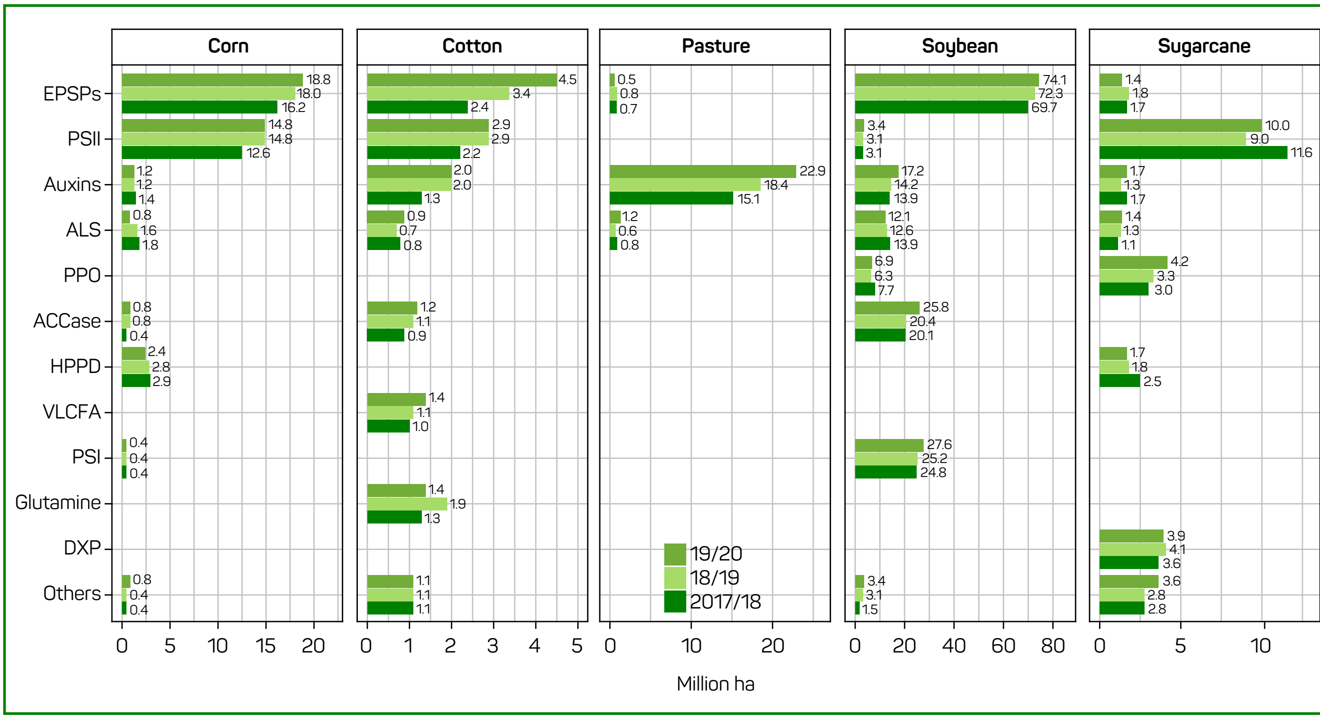
iodosulfuron-methyl	2.0	5	405.8
linuron	54.8	900	60.9
MCPA	184.3	585	315.0
mesotrione	465.6	120	3880.4
metribuzin	846.9	480	1764.4
metsulfuron-methyl	106.6	4.8	22201.7
MSMA	1885.1	2880	654.6
nicosulfuron	65.2	45	1448.2
oxadiazon	10.8	1600	6.8
oxyfluorfen	139.1	720	193.2
paraquat dichloride	16398.1	500	32796.3
pendimethalin	158.8	1000	158.8
penoxsulam	12.1	72	168.2
picloram	3827.5	582	6576.4
profoxydim	8.3	100	83.5
propanil	173.0	2880	60.1
propaquizafop	0.0	125	0.0
pyrazosulfuron-ethyl	1.0	20	50.0
pyrithiobac-sodium	20.1	98	204.7
pyroxsulam	2.6	18	145.8
quinclorac	83.0	750	110.7
quizalofop-p-ethyl	122.1	100	1221.1
quizalofop-p-tefuryl	42.0	100	420.4
saflufenacil	193.7	35	5533.3
sethoxydim	6.6	230	28.5
simazine	394.2	2000	197.1
s-metolachlor	6061.3	1440	4209.2
sulfentrazone	1991.0	470	4236.2
tembotrione	188.4	100	1884.2
triclopyr-butotyl	1926.9	680	2833.7
trifloxysulfuron-sodium	1.3	15	89.0
trifluralin	1887.4	1500	1258.3
Total	345395.8		

to 17.2 million ha (42%); EPSPs increase from 69.7 to 74.1 million ha (6%), and ALS-inhibitors decrease 13% (Figure 4). In corn, the large use increase occurred to PSI inhibitors from 12.6 to 14.8 million ha (17%) and EPSPS from 16.2 to 18.8 million ha (16 %), and a decrease of use occurred for Auxins, ALS and HPPD inhibitors (Figure 4). This decrease is associated with the increase of glyphosate use mainly as POST. In cotton, the main changes occurred for EPSPS that increase from 2.4 to 4.5 million ha (87%), PSII from 2.2 to 2.9 (32%), in the 2017/18 to 2019/020 seasons, respectively. The large change in herbicide use occurred for Auxinic herbicides, which are the main herbicides used in pastures and the increase was from 15.1 to 22.9 million ha (51%) in the 2017/18 to 2019/020 seasons, respectively. In sugarcane, PSII herbicides are the mainly used, but the use of this products decreased from 11.8 to 10.0 million ha (16%) in the 2017/18 to 2019/020 seasons, respectively (Figure 4).

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



SOURCE: Spark, 2021

Figure 4 - Estimated application of herbicide sites of action in million ha by crop in the season of 2017/18, 2018/19, and 2019/20 in Brazil.

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 sugarcane. 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% (Marsico, 1980) (Table 2). In wheat, the most used herbicides for the control of broadleaf weeds were the synthetic auxin herbicides, 2,4-D, MCPA, dicamba and picloram. On the other hand, grass species (*Avena fatua* and *Lolium* sp.) were controlled traditionally with the ACCase inhibitor herbicide diclofop-methyl, and to a lesser extent with difenzoquat, an herbicide with an unknown SOA that had been out from the market for many years now. In corn, chemical control was carried out with the use of PRE herbicides such as atrazine, alachlor, EPTC and butylate, and at POST 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, and acifluorfen-sodium and bentazon at POST for the control of broadleaf weeds. Pirifenop was also applied at POST for the control of grass weeds, particularly perennials, 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 1990s.

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	710.000
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 (2021)

During the 1980s, many new active ingredients were introduced. 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

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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 (from 118,000 to 1,470,000 ha) (Basile *et al.*, 1995). Total wheat planted was 4,750,000 ha and 5,147,000 ha in 1989 and 1994, respectively (Ministério de Agricultura, Ganadería y Pesca, 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-propargyl 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, imazethapyr), 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 clethodim) 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 herbicides was mainly represented by atrazine for the control of broadleaf weeds and alachlor, metolachlor and 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 in POST for control of both annual and perennial grass species.

Table 3 - Decade of Introduction of different herbicides and sites of action in the soybean market in Argentina

Seventies	Eighties	Nineties
Metribuzin (PS II)	Metolachlor (VLFA)	Flumetsulam (ALS)
Alachlor(VLFA)	Fomesafen (PPO)	Diclosulam (ALS)
Pirifenop (ACCase)	Fluoroglycofen (PPO)	Cloransulam (ALS)
Trifluralin (Microtubule assembly)	Fluazifop-butyl (ACCase)	Propaquizafop (ACCase)
Bentazon (PSII)	Haloxifop-methyl (ACCase)	Glyphosate* (EPSPS)
Acifluorfen (PPO)	Quizalofop-ethyl (ACCase)	Sufentrazone (PPO)
	Sethoxydim (ACCase)	Flumioxazin (PPO)
	Clethodim (ACCase)	
	Imazaquin (ALS)	

*In GR Soybean

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 (Asociación Argentina de Productores en Siembra Directa, 2021). Likewise, in 1996, genetic modified crops resistant to glyphosate (GR soybean, corn, and cotton) were introduced in the market. The adoption of GR 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 (Consejo Argentino para la Información y el Desarrollo de la Biotecnología, 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. Imidazolinone tolerant maize (imazapic), sunflower (imazapyr), and rice (imazapic+imazapyr) were introduced in 1998, 2003 and 2004, respectively. After that, Clearfield Plus sunflower with tolerance to imazapyr and imazamox was incorporated in 2010.

The adoption of GR 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 dollars (Basile *et al.*, 1995). In 2007, this total was 1.6 billion dollars, while in 2016 it reached 2.5 billion dollars (CASAFE, personal communication). The total herbicides sales represent around 1.8 billion dollars in 2008 and 2.0 billion dollars in 2019, with little variation between this time (Figure 5). Beyond the operative and economic advantages of the GR technology, ten years after its introduction the first populations of a weed resistant to glyphosate was identified. The first case was *Sorghum halepense* from the northwest of Argentina, reported by Delucchi in 2005 (Heap, 2022) and studied by Vila-Aiub *et al.* (2007). From that moment, the rate of reports of herbicide resistant weed populations was 4 cases/year, totaling 40 of which 27 are GR. This was reflected in the relative increase in selective herbicides in market from 2008 to 2019 (Figure 5), particularly related to ACCase and PPO inhibitors (Ferrari, personal communication). In 2008 glyphosate represented 80% of herbicide market, while in 2019 glyphosate sales was responsible for only 36% of commercialized herbicide (Figure 5).

4. Herbicide Use in Uruguay

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, 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, Vittori, 1975).

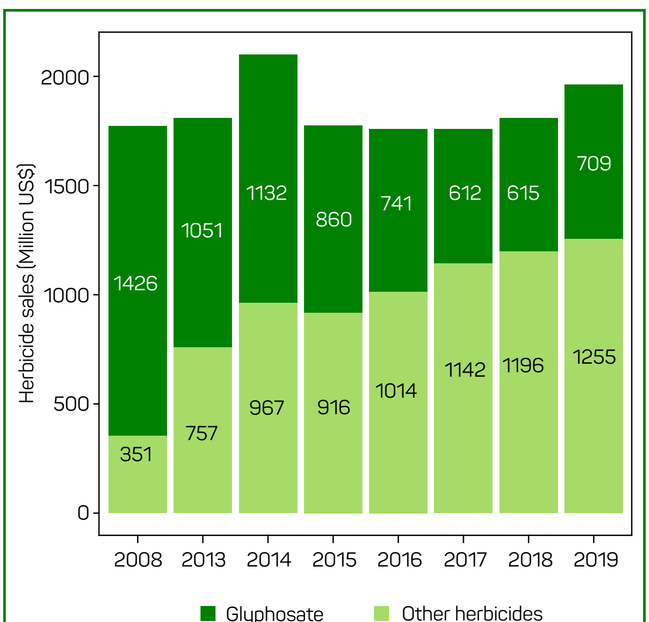


Figure 5 - Herbicides market from 2008 to 2019 in Argentina. (Data form Agrochemical Companies BASF, Syngenta and Corteva)

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, 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 (Ministerio de Ganadería, Agricultura y Pesca, 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, 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 (Ministerio de Ganadería, Agricultura y Pesca, 2021), particularly auxin herbicides used in winter crops, which dominated agriculture by that time. 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. 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, 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-tillage 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 GR 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 6A).

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 GR technology, already approved in the country, converged to accelerate adoption of no-tillage farming and to explain the shift towards GR 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-tillage continuous agriculture with GR soybean as the most important crop. Fuel and time savings in this new scheme not only reduced production costs but also enabled double cropping, and glyphosate quickly became by far the most imported and used herbicide in the country (Figure 6B).

Agriculture production and area grew importantly between 2000 and 2014 when GR soybean crop reached 1.35 million ha (Ministerio de Ganadería, Agricultura y Pesca, 2015). Concomitantly, herbicide use and imports boomed during this period (Figures 6A and 6B). No tillage and GR technology contributed to drastically change weed management approaches. Initially, weed management based on GR 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 6B). By 2010 weed management in GR soybean, which represented 65% of the total agricultural area (Ministerio de Ganadería, Agricultura y Pesca, 2015), was based almost exclusively on glyphosate and occasionally an ALS inhibitor. As a result, changes in weed species frequencies became evident (Ríos *et al.*, 2005). Around 2009 those changes were followed by concerns of farmers who argued that *Lolium multiflorum* (annual ryegrass) was no longer controlled by previous rates of glyphosate and thus herbicide rates started to be increased.

Currently, herbicide resistant weeds are one of the most important problems in Uruguayan agriculture. Glyphosate resistance have been confirmed in populations of annual ryegrass (Félix, Urioste, 2016), fleabanes (*Conyza sumatrensis* and *C. bonariensis*) (unpublished data), and

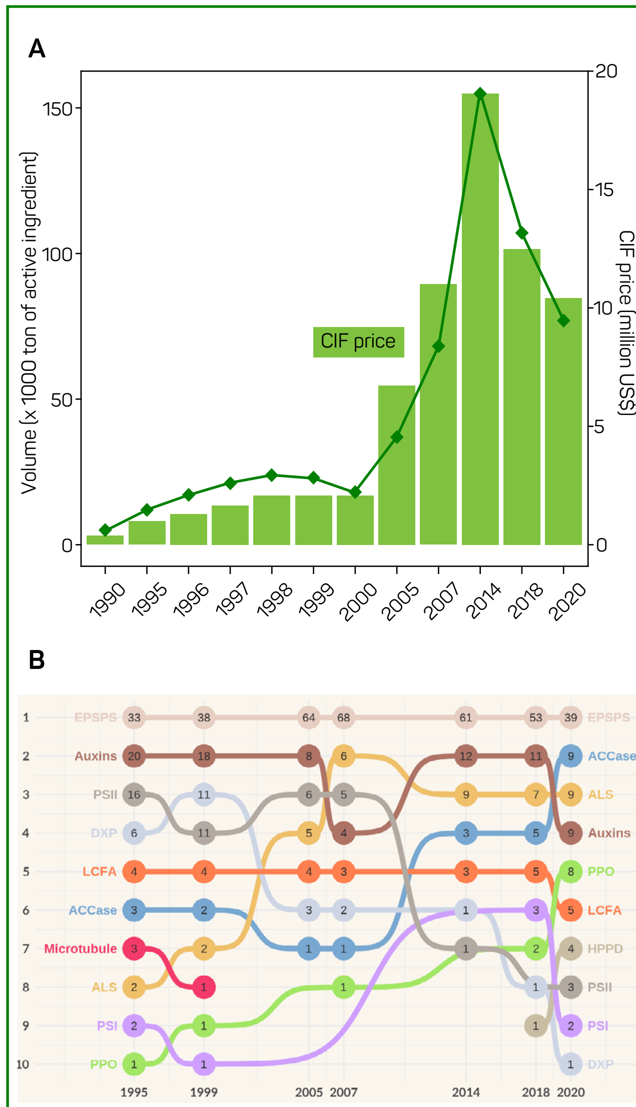


Figure 6 - Evolution of herbicide use in Uruguay. Total herbicide imports (A); and ranking of herbicide sites of action used from 1995 to 2020 (B). Values in the dots represent the percentage use of each herbicide site of action by growing season

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 6B).

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 highlighting due to its impact on pesticides demands, is the political period known as "agrarian reform" which took place between 1963 and 1973 in Chile. During this period the Chilean government assumed an important role in the development and generation of technological packages with an intensive use of pesticides (Viel, 2021).

5.1 The herbicide market between the years 1960 to 1990

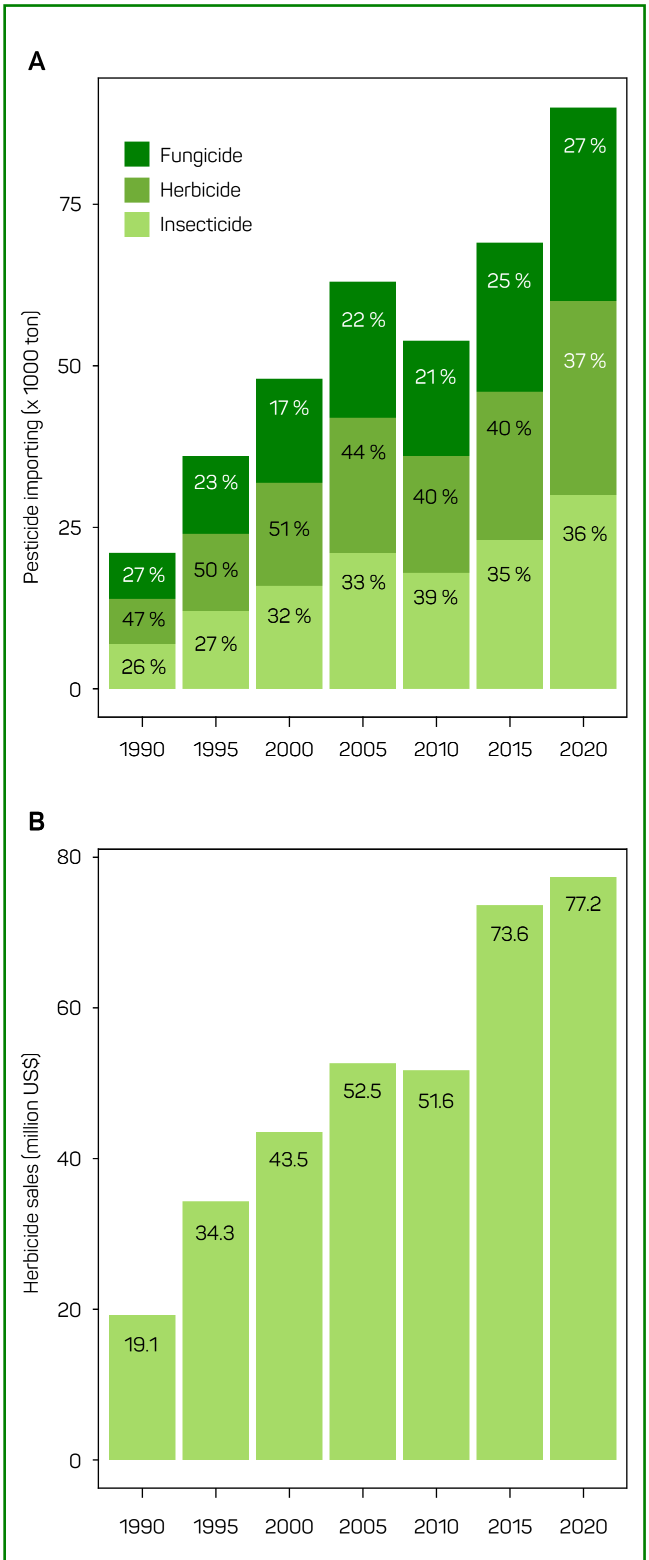
The IV agricultural Chilean census (1964-1965) shows that in the 1960s Chile had a total of 3.2 million hectares sown or planted, among which almost 40% corresponded to forage species, 35% to cereals and farms, 13% to forestry, 3.6% to industrial crops, 3.4% to vineyards, 2.7% to vegetables and flowers and 2.5% to fruit trees (República de Chile, 1969). The data collected indicated that between the years 1958 and 1963 a total of 361.2 tons of herbicide formulations were imported, corresponding to 48 different products, which are mostly systemic herbicides derived or from combinations of 2,4-D 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 their adoption in the country (Comisión Economica para America Latina, 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 and 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 of pesticides grew more than 15 times (Ormeño, 1997), reaching a value of over 44 million dollars in 1990. For this period, herbicides reached a value of almost 19 million dollars, equivalent to 42% of imported pesticides (Ministério de Agricultura, 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 decrease the dependence on labor for weed control (Kogan, 1992).

5.2 The Chilean herbicide market today

Records of agrochemical imports since the 90s show a sustained increase in the use 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 35% and fungicides with 26% (Figure 7A). 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 7B) (Ministério de Agricultura, 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 in the country (Ormeño, 1997). In summary almost 100% of the herbicides used in Chile are imported from other countries such as Argentina, China, USA, Germany and Brazil (Ministério de Agricultura, 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 a triplication of the fruit trees area, 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 and 2007.

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 (Servicio Agrícola y Ganadero, 2021). According to the latest data on pesticide sales for 2019, in the northern area of the country where fruit and vegetable are mostly produced (Atacama to Coquimbo), as well as the central area (Valparaíso to Maule) where, in addition to fruit and vegetable crops; vineyards, industrial crops and forest plantations are produced, 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



Source: Ministério de Agricultura, 2021

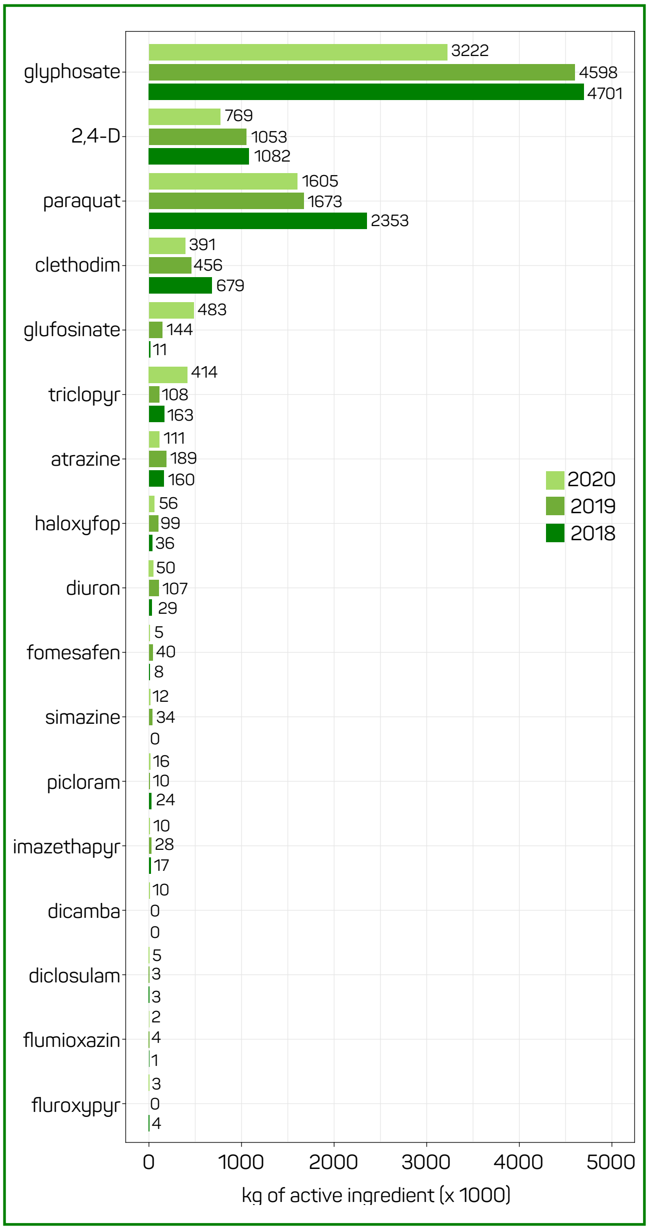
Figure 7 - Use of herbicides in Chile. Thousands of tons of pesticides (herbicides, fungicides and insecticides) imported annually in Chile (1990-2020) (A). Value of the Chilean herbicide market in millions of dollars (1990-2020) (B). Source: ODEPA. Office of agricultural studies and policies, Chilean ministry of agriculture, Pesticides import years 1990-2020.

sold herbicides together with glyphosate and paraquat are MCPA, 2,4-D, simazine, metsulfuron, pendimethalin, trifluralin, oxyfluorfen, fluoxypyr, and S-metolachlor (Servicio Agrícola y Ganadero, 2019).

The widespread use of glyphosate and paraquat in Chile is mostly explained by the fall in their prices, which began to be observed since the eighties, especially in herbicides such as paraquat, and 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, 1997). With the increasingly widespread use of herbicides, the first cases of herbicide-resistant weeds began to be reported in the early 1990s. To date, resistance to ACCase inhibitor herbicides such as haloxyfop-methyl has been described in species such as *Lolium perenne* (2001), *Lolium multiflorum* (1998), *Lolium rigidum* (1997), *Avena fatua* (1998), and *Cynosurus echinatus* (1999) in oat, canola and lupine crops. In 2001, resistance to glyphosate was described in *L. perenne* and *L. multiflorum* in vineyards and fruit trees, and in 2005 resistance to ALS inhibitors in populations of *Schoenoplectus mucronatus* and *Alisma plantago-aquatica* in rice crops was reported, 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, 2022).

6. Herbicide use in Paraguay

Agriculture in Paraguay has experienced a significant growth in the past decades. Soybean, corn and irrigated rice are the main cultivated crops. Most of the technology used in cropping systems in Paraguay is similar to that used in Brazil and Argentina (Salas, Sarubbi, 2013). Concomitantly, 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 (Oficina Consultiva y de Investigación Técnica, 2021). Paraquat, 2,4-D and glyphosate are the top used herbicides (Figure 8). Glyphosate represented nearly 50% of the total herbicide use in 2018. However, glyphosate use decreased to 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 in the future.



Source: INBIO, 2021

Figure 8 - Herbicide use in Paraguay (kg ia x 1000) in the period from 2018 to 2020.

7. Herbicide use in other South American countries

Pesticide data from local official authorities or 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. The evolution in weed management methods and land-use conversion, from pasture or degraded areas to grain crops, may promote greater use of herbicides in these countries.

Herbicide use has grown quickly in developing countries in the past two decades (Haggblade *et al.*, 2017). One main drive of herbicide use shift in SA might be the expiration of patents. This event allowed the commercialization of generic herbicides, usually with lower prices than the patented molecule. Another fact that contributed to herbicide price dropping was new herbicide production technologies and scaled-up productive capacity, which cause a significant decay in production costs (Haggblade *et al.*, 2017). Despite the greater disponibility of active ingredients, only a few had their use increased, and like for the other SA countries, this absence of increase is attributed to weed resistance to herbicides.

8. Future perspective of herbicide use in South America

The large expansion of row crops, mainly soybean, and massive adoption of no-tillage system have driven herbicide use in the countries with large agriculture areas in SA. As indicated in the brief history of the no-tillage adoption in SA presented in this review, the cost-effectiveness of herbicides for managing weeds prior to crop planting was a key factor for the evolution of this system in the early 1980s. However, currently weed populations of several species are resistant to herbicides used in burndown across different SA countries (Vidal, Merotto Jr, 1999; Leal *et al.*, 2021, Heap, 2022). This highlights the current complexity of the burndown operation in no-tillage systems. No-tillage system is of high importance for sustainable soil management and at the same time, herbicide burndown is an important basis of vegetation management in no-tillage systems that poses a high risk for the evolution of weed resistance to herbicides. This operation should be considered strategically in crop management by farmers, as well as a priority for research in relation to the development of complementary alternative technologies to herbicides seeking to provide sustainability to no-tillage systems. In addition, politic decisions on banning certain pesticides if not well analyzed could lead to other serious problems. Herbicide banning decisions such as paraquat must consider the whole scenario of weed management in agriculture for a better achievement of environment sustainability.

The introduction of herbicides with new SOA was worldwide interrupted at the beginning of the nineties

(Westwood *et al.*, 2018) due to the impacts of glyphosate and GR crops. From the 2000 new SOA for certain crops such as saflufenacil, tolpyratalato, pyroxsasulfone, mesotrione, topramezone, pinoxaden were introduced in SA, 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 enable and promote the utilization at new SOA for POST 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 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). Cultural and economic differences among SA countries will probably affect the speed at which modern technologies are adopted by different countries. Yet, production and society signals across SA 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 detrimental impact on food production systems ("weed interference") as well as to work towards more effective and ecofriendly alternatives for weed management. Weed management alternatives are currently being challenged to incorporate technology-based decision tools such as environmental data series to adjust weed emergence models with the aim to optimize herbicide spraying. 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 in the 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 SA agriculture in the last decades. Intensification of agriculture, no-tillage, patent expirations, glyphosate resistant crops, and herbicide resistant weeds were the most important drivers of herbicide use changes in SA. Glyphosate has been the most used herbicide across different agriculture systems and weed resistance to this herbicide is challenging current weed control practices. Since no new broad-spectrum herbicide SOA has been available for a while the use of older herbicides is increasing, although sometimes used in different ways or associated with transgenic traits.

In modern agriculture, weed management is one of the key pieces leveraging evolution and development of new technologies. Such new technologies like sensors, autonomous machines, and molecular RNAi could revolutionize weed control in the future. However, currently, and for years to come, food production will most probably still largely depend on herbicides for weed management. Yet, there are a diversity of technologies for weed management underutilized in SA which can be strategically and synergistically used with herbicides. The use and implementation of truly integrated weed management in SA is needed to maximize sustainable food production.

Author's contributions

All authors read and agreed to the published version of the manuscript. AMJ, DLPZ, and MCO: conceptualization of the manuscript and development of the methodology. AMJ, DLPZ, JS, MAG e RF: data collection and curation. AMJ, MCO, JS, MAG, RF and GMT: data analysis and interpretation. AMJ and DLPZ: project administration. AMJ: supervision. AMJ, MCO, DLPZ, JS, MAG, and RF: writing the original draft of the manuscript. AMJ, MCO, MAG and GMT: writing, review and editing.

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References

Adegas FS, Gazziero DLP, Voll E. [Glyphosate resistant transgenic soybean as tool for weed management and sustainable production: Glyphosate, sustainable use]. Botucatu: Fundação de Estudos e Pesquisas Agrícolas e Florestais; 2012. Portuguese

Almeida FS. [Weed control]. In: Fundação Instituto Agronômico do Paraná - IAPAR. [Direct planting in the state of Paraná]. Londrina: Fundação Instituto Agronômico do Paraná; 1981. (Circular, 23). Portuguese

Asociación Argentina de Productores en Siembra Directa – AAPRESID. [Weeds]. Rosario: Asociación Argentina de Productores en Siembra Directa; 2021[access November 21, 2021]. Spanish. Available from: https://www.aapresid.org.ar/rem/malezas#pid=1

Basile E, Castelli C, Vicien C, Palma L. [Agrochemicals use in 1994]. Buenos Aires: Ministerio de Obras y Servicios Públicos; 1995. Spanish

Bianchi MA. [Weed management in Roundup Ready soybean in Rio Grande do Sul]. Cruz Alta: Fundacep; 2005. (Informativo Fundacep 14). Portuguese

Bonjour AA. [The application of chemicals in the fight against weeds]. La Estanzuela: Inisitituto Nacional de Investigación Agropecuaria; 1949. (Phytotechnical file of Uruguay vol. 4, no. 1). Spanish

Bonjour AA. [Weeds in the rotation trial of the phytotechnic institute "La Estanzuela"]. Montevideo: Inisitituto Nacional de Investigación Agropecuaria; 1935. (Phytotechnical file of Uruguay) Spanish

Camargo ER, Zapiola ML, Avila LA, Garcia MA, Plaza G, Gazziero D *et al.* Current situation regarding herbicide regulation and public perception in South America. Weed Sci. 2020;68(3):232-9. Available from: https://doi.org/10.1017/wsc.2020.14

Carbonari CA, Velini ED. Risk assessment of herbicides compared to other pesticides in Brazil. Adv Weed Sci. 2021;39:1-6. Available from: https://doi.org/10.51694/AdvWeedSci/2021;39:00006

Cerdeira AL, Gazziero DLP, Duke SO, Matallo MB. Agricultural impacts of glyphosate-resistant soybean cultivation in South America. J Agric Food Chem. 2011;59(11):5799-807. Available from: https://doi.org/10.1021/jf102652y

Comisión Economica para America Latina – Cepal. [Use of pesticides in Chile]. Chile: United Nations; 1966. Spanish

Companhia Nacional de Abastecimento – Conab. [Grain harvest bulletin]. Brasília: Companhia Nacional de Abastecimento; 2022[access November 21, 2021]. Portuguese. Available from: https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos

Consejo Argentino para la Información y el Desarrollo de la Biotecnología – ARGENBIO. [Transgenic crops in Argentina and in the world]. Buenos Aires: Consejo Argentino para la Información y el Desarrollo de la Biotecnología; 2021. Spanish. Available from: https://www.porquebiotecnologia.com.ar/Cuadernos/El_Cuaderno_43.pdf

Empresa Brasileira de Pesquisa Agropecuária – Embrapa. [Soybean production technologies: central region of Brazil]. 9th ed. Londrina: Embrapa Soja; 2005. Portuguese

Ernst O, Siri-Prieto G. [Agriculture in Uruguay: its trajectory and consequences]. Proceedings of the II Simposio Nacional de Agricultura; 2011; Paysandú, Uruguay. Montevideo: Universidad de la República; 2011. p. 149-63. Spanish.

Félix E, Urioste S. [First report of glyphosate resistance in *Lolium multiflorum* Lam populations in Uruguay and their susceptibility to ACCase herbicide inhibitors] [thesis]. Montevideo: Universidad de la República; 2016. Spanish.

Food and Agriculture Organization of United Nations – FAO. FAOStats: Crops and livestock products. Rome: Food and Agriculture Organization of United Nations; 2022[access March 12, 2022]. Available from: https://www.fao.org/faostat/en/#data/QCL

Gaines TA, Slavov GT, Hughes D, Küpper A, Sparks CD, Oliva J *et al.* Investigating the origins and evolution of a glyphosate-resistant weed invasion in South America. Mol Ecol. 2021;30(21):5360-72. Available from: https://doi.org/10.1111/mec.16221

Garcia MA, Meneses LV, Kaspary TE. Weed problems in uruguayan agriculture: evolution and current situation. Outl Pest Manag. 2021;32(5):203-7. Available from: https://doi.org/10.1564/v32_oct_05

Gazziero DLP, Adegas FS, Fornarolli D, Vargas L, Karam D, Balbinot Jr AA, Voll E. [An alert about weed resistance to glyphosate]. Cuiabá: Congresso Brasileiro de Soja; 2012. Portuguese

Gazziero DLP, Adegas FS, Voll E. [No-tillage farming in Brazil and glyphosate: Glyphosate]. Botucatu: Fundação de Estudos e Pesquisas Agrícolas e Florestais; 2009. Portuguese

Gazziero DLP, Almeida FS, Rodrigues BN, Oliveira V. [Recommendations for weed control in soybean crop]. Technical communication 21. Londrina: Embrapa Soja; 1983. Portuguese

Gimenez A, Rios A. [Evaluation of phytotoxicity of herbicides applied in stages after tillering of wheat]. Jornada Cultivos de Invierno. Montevideo: Instituto Nacional de Investigación Agropecuaria; 1993. p9-11. Spanish

Haggblade S, Minten B, Pray C, Reardon T, Zilberman D. The herbicide revolution in developing countries: patterns, causes, and implications. Eur J Dev Res. 2017;29(3):533-59. Available from: https://doi.org/10.1057/s41287-017-0090-7

Heap I. The international herbicide-resistant weed database. Weedscience. 2022[access November 21, 2021]. Available from: https://www.weedscience.org

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – Ibama. [Pesticides information panels]. Brasília: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis; 2020[access November 21, 2021]. Portuguese. Available from: http://www.ibama.gov.br/agrotoxicos/paineis-de-informacoes-de-agrotoxicos#inicio

Instituto de Biotecnologia Agrícola – INBIO. [Home]. Asunción: Instituto de Biotecnologia Agrícola; 2021[access Mês dia, ano]. Spanish. Available from: https://www.inbio.org.py/

Kogan M. [Herbicides: advances in herbicide technology and control strategies]. Providencia: Centro de Información de Recursos Naturales; 1992. Spanish

Kudsk P, Streibig JC. Herbicides: a two-edged sword. Weed Res. 2003;43(2):90-102. Available from: https://doi.org/10.1046/j.1365-3180.2003.00328.x

Lazen S. [Herbicides in fruit orchards]. In: Proceding of the 21th Agronomic conference of Chile; 1970; Santiago, Chile. Spanish.

Leal JFL, Borella J, Souza AS, Oliveira GFPB, Langaro AC, Pinho CF. Sourgrass and fleabane are controlled by haloxyfop-p-methyl and cloransulam-methyl interaction and interval of application. Adv Weed Sci. 2021;39:1-7. Available from: https://doi.org/10.51694/AdvWeedSci/2021;39:00010

Marchesi, E. [Direct sowing in Uruguay]. In: Proceding of the Jornada Nacional de Siembra Directa; 1993; Mercedes. Mercedes: Asociación Uruguaya pro Siembra Directa; 1993. Spanish. p. 27-41.

Marsico OJV. [Herbicides and fundamentals of weed control]. Buenos Aires: Hemisferio Sur; 1980. Spanish

Martínez-Galarraga J, Rodríguez Miranda A, Siniscalchi S, Willebald H. [The regional distribution of production in Uruguay, 1908-1975: methodological proposal and sources]. Montevideo: Udelar; 2019. Spanish

Merotto A, Goulart ICGR, Nunes AL, Kalsing A, Markus C, Menezes VG *et al.* Evolutionary and social consequences of introgression of nontransgenic herbicide resistance from rice to weedy rice in Brazil. Evol Appl. 2016;9(7):837-46. Available from: https://doi.org/10.1111/eva.12387

Ministério de Agricultura (CL). [Pesticides import years 1990-2020]. Santiago: Ministério de Agricultura; 2021. Spanish. Available from: https://www.odepa.gob.cl/estadisticas-del-sector/comercio-exterior

Ministério de Agricultura, Ganadería y Pesca (AR). [Agricultural estimates]. Buenos Aires: Ministério de Agricultura, Ganadería y Pesca; 2021. Spanish. Available from https://datosestimaciones.magyp.gob.ar/reportes.php?reporte=Estimaciones

Ministerio de Ganadería, Agricultura y Pesca (UY). [2015 Agricultural statistic yearbook]. Montevideo: Ministerio de Ganadería, Agricultura y Pesca; 2015. Spanish.

Ministerio de Ganadería, Agricultura y Pesca (UY). [Crop day 1: 1969]. Colonia: CIAAB. 1969. Spanish. 169 p.

Ministerio de Ganadería, Agricultura y Pesca (UY). [Herbicide registration list 1977 – 2021]. Montevideo: Ministerio de Ganadería, Agricultura y Pesca; 2021. Spanish.

Moreno-Moreno J-J, Morente FV, Dias MTS. Assessment of the operational and environmental efficiency of agriculture in Latin America and the Caribbean. Agric Econ Czech. 2018;64(2):74-88. Available from: https://doi.org/10.17221/260/2016-AGRICECON

Oficina Consultiva y de Investigación Técnica – OCIT. [Webpage]. Asunción: Oficina Consultiva y de Investigación Técnica; 2021. Spanish. Available from: https://www.ocitinternacional.com.py/

Oliveira MC, Lencina A, Ulguim AR, Werle R. Assessment of crop and weed management strategies prior to introduction of auxin-resistant crops in Brazil. Weed Technol. 2021;35(1):155-65. Available from: https://doi.org/10.1017/wet.2020.96

Ormeño J. [Evolution in the use of herbicides in Chile]. Tierra Adentro. 1997;(27):10-3. Spanish

Pagnoncelli FDB, Trezzi MM, Salomão HM, Hartmann KC, Pereira PB, Gonzalez-Andujar JL. Demographics of glyphosate-resistant and susceptible Italian ryegrass populations from Paraná. Adv Weed Sci. 2021;39:1-7. Available from: https://doi.org/10.51694/AdvWeedSci/2021;39:00011

Perea C, Vittori E. [New herbicides for winter crops]. Colonia: CIAAB; 1975. Spanish.

Plan Agropecuario. [Weeds]. Rev Plan Agropec. 1986;14(36):29-31. Spanish.

Queiroz ARS, Delatorre CA, Lucio FR, Rossi CVS, Zobiole LHS, Merotto A. Rapid necrosis: a novel plant resistance mechanism to 2,4-D. Weed Sci. 2020;68(1):6-18. Available from: https://doi.org/10.1017/wsc.2019.65

República de Chile. [IV national agricultural census, agricultural year 1964-1965]. Santiago: República de Chile; 1969. Spanish.

República del Uruguay. [Law N° 39, from November 9, 1911. Creates a central agricultural defense commission]. Diario Oficial de la República Oriental del Uruguay. Nov 9, 1911. Spanish.

Ríos A, Fernández G, Collares L. [Study of the weed communities associated to direct drilling systems in Uruguay]. In: proceeding of the Seminario-Taller Iberoamericano "Resistencia a Herbicidas y Cultivos Transgénicos"; 2005; Colonia del Sacramento. Colonia del Sacramento: Instituto Nacional de Investigación Agropecuaria; 2005. Spanish. p. 129-41.

Salas P, Sarubbi H. [Weed management in soybean crop in Paraguay]. Technical series 204, Uruguay: Instituto Nacional de Investigación Agropecuaria; 2013. Spanish.

Santos G, Oliveira RS, Constantin J, Francischini AC, Machado MFPS, Mangolin CA *et al. Conyza sumatrensis*: a new weed species resistant to glyphosate in the Americas. Weed Biol Manag. 2014;14(2):106-14. https://doi.org/10.1111/wbm.12037

Servicio Agrícola y Ganadero – SAG. [List of authorized pesticides]. Santiago: Servicio Agrícola y Ganadero; 2021. Spanish. Available from: https://www.sag.gob.cl/ambitos-de-accion/insumos-y-productos-silvoagricolas/76/registros

Servicio Agrícola y Ganadero – SAG. [Sales declaration of pesticides for agricultural use year 2019]. Santiago: Servicio Agrícola y Ganadero; 2019. Spanish. Available from: https://www.sag.gob.cl/ambitos-de-accion/plaguicidas-y-fertilizantes/78/registros

Spark. Spark smarter decisions. Valinhos: Spark; 2021. Portuguese. Available from: https://spark-ie.com.br/

Trindade FJ, Fulginiti LE. Is there a slowdown in agricultural productivity growth in South America? Agric Econ. 2015;46(S1):69-81. Available from: https://doi.org/10.1111/agec.12199

Ulguim AR, Fruet BL, Merotto Junior A, Silva AL. Status of weed control in imidazolinone-herbicide resistant rice in Rio Grande do Sul. Adv Weed Sci. 2021;39:1-7. Available from: https://doi.org/10.51694/AdvWeedSci/2021;39:00007

Vargas L, Adegas F.S, Gazziero DLP, Karam D, Agostineto D, Silva WT. [Weed resistance in Brazil: history, distribution, economic impact, management and prevention] In: Meschede DK, Gazziero DLP. [The glyphosate era: agriculture, environment and man]. Londrina: Midiograf; 2016. Portuguese

Vidal RA, Merotto Jr. A. [Wild poinsettia resistance to acetolactate synthase inhibitors herbicides]. Planta Daninha. 1999;17(3):367-73. Portuguese. Available from: https://doi.org/10.1590/S0100-83581999000300005

Viel NEG. [Chilean agrarian reform: causes, phases and balance]. Santiago: University of Chile; 2021. Spanish. Available from: https://doi.org/10.34720/yp20-2f44

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CM, Powles SB. Evolution of glyphosate-resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci. 2007;55(6):566-71. Available from: https://doi.org/10.1614/WS-07-053.1

Vila-Aiub MM, Vidal RA, Balbi MC, Gundel PE, Trucco F, Ghersa CM. Glyphosate-resistant weeds of South American cropping systems: an overview. Pest Manag Sci. 2008;64(4):366-71. Available from: https://doi.org/10.1002/ps.1488

Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC *et al.* Weed management in 2050: perspectives on the future of weed science. Weed Sci. 2018;66(3):275-85. Available from: https://doi.org/10.1017/wsc.2017.78