Production of agrocommodities and consumption of agrochemicals in Uruguay: its repercussions for aquatic systems

Produção de agrocommodities e consumo de agroquímicos no Uruguai: suas repercussões para os sistemas aquáticos

DOI: 10.34188/bjaerv5n1-050

Recebimento dos originais: 25/11/2021
Aceitação para publicação: 28/01/2022

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ABSTRACT

The objective of this study is to relate the amount of phosphorus (P) provided by agrochemicals (herbicides and phosphate fertilizers) to soil sown with genetically modified (GM) crops (soybeans and maize) with total phosphorus (TP) in waters of agricultural basins in Uruguay, South America. With this aim, the number of soybean and maize events resistant to glyphosate and glufosinate-ammonium, the total area sown with these GM crops, herbicides and phosphate fertilizers consumption, and TP in the main river of the country in the 2010-2019 period were considered. We found out that the relationship of the annual average of TP with P via herbicides is robust and statically significant, and the relationship with P contribution via fertilizers is strong but no statically significant. Therefore, herbicides must be taken into account as a probable cause of eutrophication of aquatic systems in order to achieve environmental standards.

Keywords: GM crops, fertilizers, glyphosate, glufosinate-ammonium, total phosphorus, aquatic systems.

RESUMO

O objetivo deste estudo é relacionar a quantidade de fósforo (P) fornecida por agroquímicos (herbicidas e fertilizantes fosfatados) em solo semeado com culturas geneticamente modificadas (GM) (soja e milho) com fósforo total (PT) em águas de bacias agrícolas no Uruguai, América do Sul. Com este objetivo, o número de eventos de soja e milho resistentes ao glifosato e glufosinato-amônia, a área total semeada com essas culturas GM, consumo de herbicidas e fertilizantes fosfatados e PT no principal rio do país no período 2010-2019 foram considerados. Descobrimos que a relação da média anual de PT com P via herbicidas é robusta e estatisticamente significativa, e a relação com a contribuição de P via fertilizantes é forte, mas não estatisticamente significativa. Portanto, os herbicidas devem ser considerados como uma provável causa de eutrofização dos sistemas aquáticos para atingir os padrões ambientais.

Palavras-chave: culturas GM, fertilizantes, glifosato, glufosinato de amônio, fósforo total, sistemas aquáticos .

1 INTRODUCTION

Water pollution has increased worldwide as a result of anthropic activities, in particular from agriculture. In many countries, the impact of this activity has exceeded that of pollution of industries and settlements, becoming the main factor of degradation of inland and coastal waters (FAO and IWMI, 2017). Such is the case of Uruguay, where environmental externalities are strongly associated with the change in land use and management, driven by a system of intensive cultivation mainly of genetically modified (GM) crops (soybean and maize).The technological package applied includes, among others, fertilizers and herbicides (Arrieta et al., 2018; Caride et al., 2012; Pengue, 2009) with a high content of phosphorus (P). These agrochemicals can reach water bodies through different routes and impact the quality of water. In the country, other agricultural activities, which are also relevant sources of P, are carried out, such as livestock farming and dairy production. There is indeed a contribution of P coming from direct excreta and manures. However, these activities have not had a significant increase in the last decade. For example, the number of cattle increased by only 3.3% while the number of sheep decreased by 14.4% in the 2011-2018 period (MGAP-DIEA, 2019).

Soybeans and corn, along with sorghum, are summer crops grown in Uruguay, but the area of sorghum is negligible compared with the other two. Sowing of these monocultures leads to selective extraction of nutrients from the soil requiring replacement through fertilizer (Pengue, 2009; Phélinas and Choumert, 2017). In Uruguay, the most widely used fertilizers are phosphate fertilizers. In general, these agrochemicals are applied directly to the soil surface without mixing, which leads to a high P stratification. Besides, successive annual applications of fertilizers leave phosphate concentrations that reduce the soil capacity of retaining consequent applications (Gimsing et al., 2004; Munira et al., 2018). For example, in Uruguay, a high concentration and proportion of soluble reactive P, predominantly phosphate ions and a more readily for biological use form, was found in the composition of total P (TP) in the Santa Lucía River, a tributary of the Río de la Plata (Aubriot et al ., 2017; Barreto et al., 2017; Chalar et al., 2017). This is consistent with recent developments that have shown that a significant portion of P losses can be found in the dissolved form (Reid et al., 2018).

On the other hand, the most widely used herbicides are glyphosate and glufosinate-ammonium. These herbicides are phosphonic acids or phosphonates that are characterized by a carbon-phosphorus bond (C-P) (Hove-Jensen et al., 2014; Ternan et al., 1998). Thus, the final decomposition of both herbicides causes the release of P into the environment. The phosphonates have a high affinity for mineral fractions, such as clays, goethite or iron, and aluminium oxides (De Gerónimo et al., 2018; Piccolo and Celano, 1994; Vereecken, 2005; Waiman et al., 2013; Xu et al., 2016; Zhao et al., 2009). Due to this affinity, several researchers point out that phosphate and phosphonates can compete for the same adsorption sites in different soil types (Borggaard and Gimsing, 2008; Gimsing et al., 2004; Gimsing and Borggaard, 2001; Laitinen et al., 2009; Munira et al., 2016; Sasal et al., 2015; Xu et al., 2016; Yu et al., 2013; Zhao et al., 2009).

There is no agreement in the literature on the means of transport of phosphonates and their metabolites to ground and surface waters. While some researchers claim that the leaching potential is limited (Aguilera et al., 2019; Faber et al., 1997; Fomsgaard et al., 2003; Munira et al., 2016; Pérez et al., 2011), others indicate the opposite (Aguilar et al., 2010; Kjær et al., 2011; Landry et al., 2005; Sasal et al., 2015), especially in soils historically fertilized (Simonsen et al., 2008). In turn, the runoff would take soil particles with the herbicides adsorbed to water bodies, where they can be desorbed, biodegraded and accumulated in the bottom sediment (Aparicio et al., 2013; Laitinen et al., 2009; Peruzzo et al., 2008). But regardless of the means of transport, these herbicides and their metabolites have been systematically found in Rio de la Plata Basin, in surface waters

(Aparicio et al., 2013; Bonansea et al., 2017; Garrido de Oliveira et al., 2019; Pérez et al., 2017; Sasal et al., 2015, 2010) and shallow lakes sediments (Castro Berman et al., 2018). In the processes, rainfall has significant influence (Arunakumara et al., 2013; Hébert et al., 2019; Laitinen et al., 2009; Peruzzo et al., 2008; Sasal et al., 2015), especially extreme events (Carpenter et al., 2017; Napoli et al., 2017). These events have become more frequent in the last decade (Bidegain et al., 2017). However, despite the importance of the issue, not only regionally but also worldwide, herbicides have been scarcely taken into account as a source of P in freshwater systems in agricultural watersheds (Borggaard and Gimsing, 2008; Hébert et al., 2019).

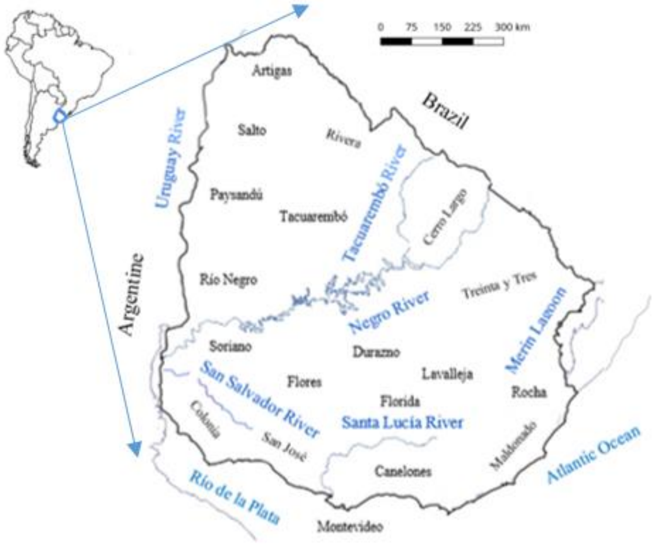
The objective of this study is to relate the amount of P provided by agrochemicals (herbicides and phosphate fertilizers) to soil sown with GM crops (soybeans and maize) to total phosphorus (TP) in waters of agricultural basins. TP concentration in water is one of the most robust and studied eutrophication indicators (Aubriot et al., 2017). To estimate the consumption of P, we used the area sown and the production of soybean and maize as well as herbicides importations. Data collected from national institutions allowed us to systematize key information to advance in the correct management of GM crops. The analysis of the Uruguayan case may afford an insight into the environmental implications of agricultural land use and into the need to focus efforts on controlling the use of herbicides as a driving factor of eutrophication and deterioration of water quality.

2 METHODOLOGY

2.1 STUDY AREA

The study area is located in South America between the 30th and 35th parallels South latitude and the 53rd and 58th meridians West longitude, and comprises a total area of 176. 215 km^2 (Figure 1).

Figure 1. The main Uruguayan rivers and the nineteen Departments of the country.



The country is part of the Río de la Plata temperate grassland ecosystems in the south-eastern region of South America of the so-called Pampa Biogeographic Province (Cabrera and Willink, 1973; Morrone, 2006; Morrone, 2001), and is one of the main agricultural areas worldwide (Soriano, 1991). The mean annual temperature is 17.5 ºC. Uruguay lacks clear seasonality in rainfall, and the annual precipitation varies from 1500 mm in the north to 1100 mm in the south (Bidegain et al., 2017). Mollisols are the dominant soils (Baldi and Paruelo, 2008). The use of land includes summer crops, double cultivation (two agricultural cycles per season), perennial forage resources, forestation, and native woodland (Baeza et al., 2014).

2.2 DATA SOURCES AND ANALYSIS

The variables chosen were: a) herbicide-resistant events approved in Uruguay; b) sown area; c) production; d) contributions of P from fertilizers and herbicides; e) extraction of P by harvest, and f) total P in water in different basins. The period analysed is from 2010 to 2019.

All graphs are self-made. They were carried out with systematized information collected in the detailed databases in each of the selected variables.

The accumulated number of soybean and maize events resistant to glyphosate and glufosinate-ammonium approved has been established to know the relationship between herbicides and crops. The data were collected from the National Biosafety Cabinet of Uruguay (GNBio) (http://portales.mgap.gub.uy/sites/default/files/multimedia/ resumen_vegetales_gm_en_uruguay_jun20_comerciales.pdf, accessed 05/08/20).

The area sown with soybean and maize as well as the production of grains were estimated. The data have been collected from the Ministry of Agriculture, Livestock, and Fisheries of Uruguay (MGAP) (www.mgap.gub.uy, accessed 23/07/2020).

To satisfy the demand for P extraction by grains, producers need to fertilize annually. As there is no information about the real consumption of phosphate fertilizers specified by farmer, it was assumed that all of them fertilize in the same way. Therefore, to estimate the phosphate contributions from fertilizers to soybean and corn crops, the frequent dose of 40 kg of phosphate (P_2O_5) per hectare and per year has been used, where $P = 0.437 \times P_2O_5$.

The extraction rates calculated by Cruzate and Casas (2009) were used to estimate the extraction of P (kg per ton of grain produced) by grains (soybeans = 5.40 kg/ton, and maize = 2.64 kg/ton). This information was then related to the P supplied by fertilizers to estimate the remaining phosphorus of these agrochemicals. In other words, we made an estimate: P contribution via fertilizers – P extraction via grains. This estimate of the nutrient balance responds to the black box concept. Therefore, it does not take into account the transformations of nutrients either in the soil-plant system or from washing or erosion (Ciampitti and Garcia, 2008).

As there is neither information on the actual herbicide consumption by crop nor on the sown area discriminated by event, we used glyphosate and glufosinate-ammonium imports to estimate the P contribution from herbicides. To calculate it, we considered the P rate in the herbicides' molecular masses. The percentage of P in glyphosate mass is 18.3%, and that of glufosinate-ammonium is 17.1%. The import data have been collected from the Supply Control Division of MGAP (https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/datos-y-estadisticas/datos/importaciones-productos-fitosanitarios, accessed 06/08/2020).

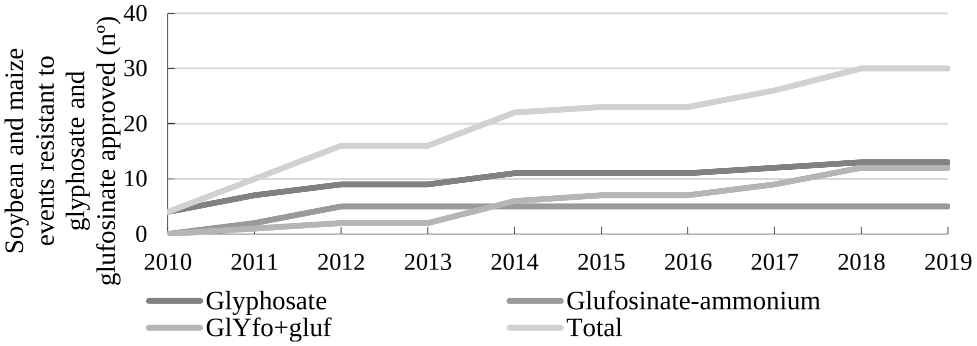
Next, the annual average of TP concentration in four basins of Uruguay was systematized: Uruguay River Basin, Santa Lucía River Basin, Negro River Basin, and Merín Lagoon Basin (Figure 1). All of them have an area sown with soybean and maize crops. For Santa Lucía River Basin and Merín Lagoon Basin the data cover the whole basin. For the Uruguay River Basin, the records include the Uruguay River and the San Salvador River, and for the Negro River Basin, the records include the Negro River and the Tacuarembó River. The 2014-2019 period was chosen because in most cases the registrations do not start in the same year but after 2010. The data have been collected from the National Environment Directorate of Uruguay (https://www.dinama.gub.uy/oan/datos-abiertos/calidad-agua/, accessed 12/08/2020). Finally, TP is related to the P supplied by agrochemicals (herbicides and fertilizers) using the excel program. Due to the small amount of data available, the sample size (N) was calculated in order to know the significance of the linear correlation coefficient with $\alpha = 0.05$; $\beta = 0.2$, and a two-sided approach.

3 RESULTS AND DISCUSSION

3.1 APPROVED HERBICIDE-RESISTANT SOYBEAN AND MAIZE EVENTS

The number of maize and soybean events approved from 2010 to 2019 is 38; 16 of soybean and 22 of maize. Among the characteristics of these events, resistance to herbicides stands out, resistance to glyphosate and glufosinate-ammonium representing the vast majority, 30 (85.7%). But, mainly, the number of events resistant to glyphosate plus glufosinate-ammonium increased. The greatest increase occurred between 2010 and 2012, where the number of approved events multiplied by four (Figure 2). This is consistent with what happens worldwide, where herbicide tolerance is the most distinctive trait, mostly glyphosate/glufosinate-ammonium tolerant (Demonte et al., 2018; Rojas Arias et al., 2017). Furthermore, there are two soybean events resistant to glyphosate and dicamba, three resistant to glyphosate, glufosinate-ammonium and 2,4-D, one resistant to glyphosate and isoxaflutole, and one resistant to glyphosate, glufosinate and isoxaflutole. On the other hand, in the approved maize events there are only five resistant to Lepidoptera, one resistant to Lepidoptera and 2,4-D, and one resistant to glyphosate, glufosinate and 2,4-D. Besides, it should be noted that the new events coexist with those previously authorized and, therefore, seeded.

Figure 2. Soybean and maize events approved in Uruguay resistant to glyphosate, glufosinate-ammonium, and glyphosate +glufosinate-ammonium (nº).

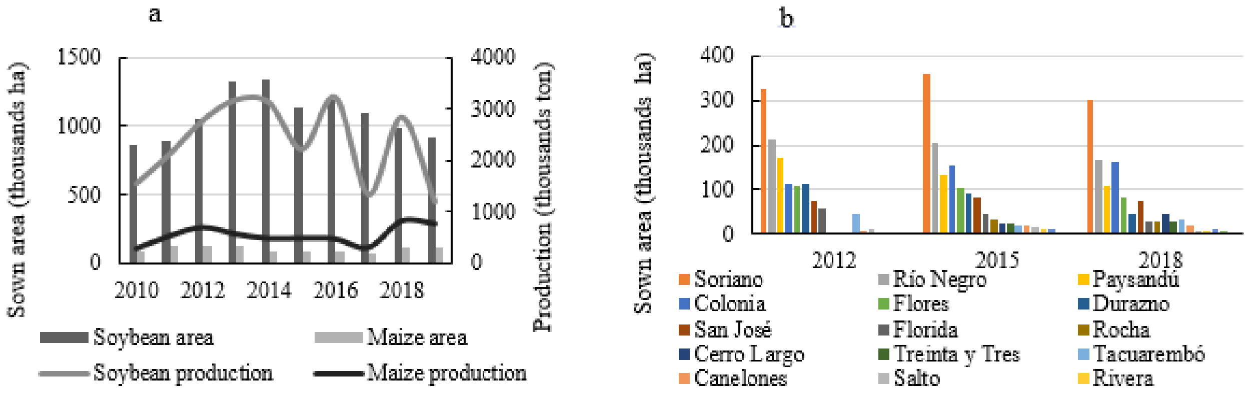


3.2 SOWN AREA

The area sown with soybean increased by 10.6% while that of maize increased by 60.7%. However, the soybean area far exceeds the maize area (Figure 3A). In total, the area sown with GM crops increased by 11% between 2010 and 2019. The largest soybean area was seeded between 2013 and 2014, and the largest maize area was sown in 2019. These variations are linked to fluctuations in grain prices in international markets. The variations in production were mainly due to climate-related reasons that affected yields. However, while the area seeded with soybean slightly increased, production decreased (Figure 3a).

The increase in the sown area occurs at the expense of expansion towards the northeast region of the country. Thus, in the last two years, while in the Departments (Figure 1) on the Uruguay River and Santa Lucía River basins the area decreased, in the northeast departments on the Negro River Basin it increased. However, the largest sown area is concentrated in the traditionally agricultural western region (Figure 3b).

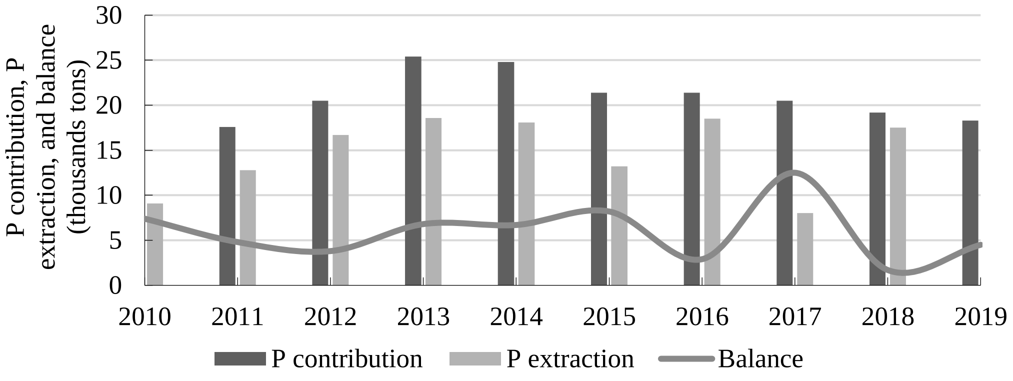
Figure 3. a. Sown area (thousands of ha) and production (thousands of tons) of soybeans and maize, 2010 - 2019. b. Summer crops sown area by Departments (thousands of ha).



3.3 P CONTRIBUTIONS FROM FERTILIZERS AND HERBICIDES

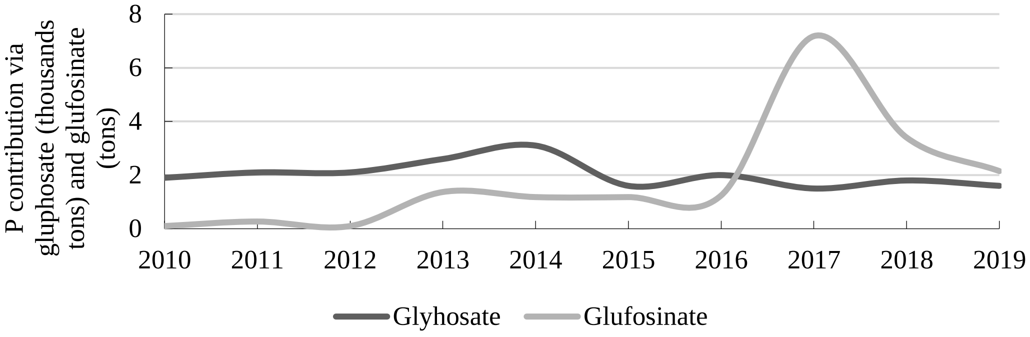
The input of P through fertilizers increased by 11%, depending on the sown area. However, due to the advance of crops towards the northeast region, with soils comparatively less fertile than those in the west, fertilizer consumption is likely to be higher. At the same time, P extracted in an annual grain harvest increased by 51.7%, reaching its maximum value in 2013. However, the estimated balance (the difference between the P contributed by the average consumption of fertilizers and the one extracted in grain production) is positive in the whole period (Figure 4). This agrees with the results of the studies (already cited) carried out in the Santa Lucia River Basin. (Aubriot et al., 2017; Barreto et al., 2017; Chalar et al., 2017). However, the current intensification of agriculture should be taken into account. For example, in 2018, 87% of the area sown with winter crops (mainly wheat and barley) was used for summer crops (Dirección de Estadística Agropecuaria, 2019). Thus, it is very likely that, as intensive agriculture predominates in the western region (the most fertile in the country), the higher entry of P via fertilizers is offset by a greater extraction of P in grains.

Figure 4. P contribution via fertilizers, P extraction in grains by harvest, and their difference (balance) (thousands of tons).



The estimated input of P via glyphosate decreased by 15.8%, and the estimated input of P via glufosinate-ammonium increased by 2050% in the period analysed (Figure 5).

Figure 5. P contribution via glyphosate (thousands of ton), and glufosinate-ammonium (tons).

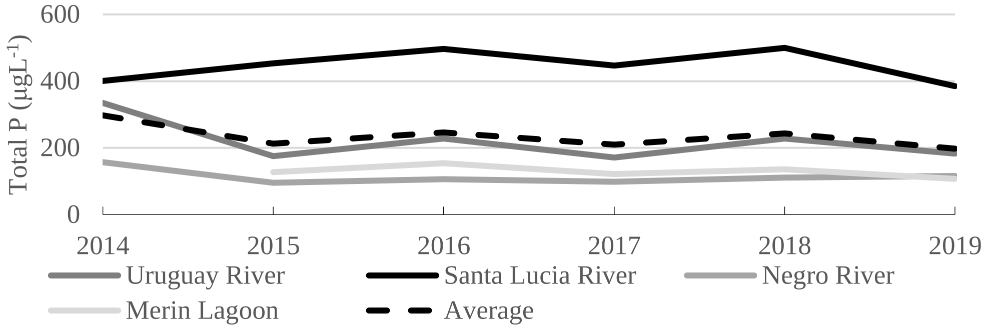


However, due to the difference in scale in the consumption of both herbicides, the total contribution of P from phosphonates decreased by 15.7%. This result is not consistent with the increase in the area planted (Figure 3). However, it should be considered that in the area sown there are events that are not resistant to glyphosate and glufosinate-ammonium. Besides, the increase in crops resistant to both glyphosate and glufosinate-ammonium allowed farmers to apply both herbicides. Thus, they use the last herbicide to combat the proliferation of glyphosate-resistant weeds. This explains the high increase in the consumption of glufosinate-ammonium.

3.4 TOTAL P

The annual averages of TP concentration registered in four river basins are far higher than the standard established in the country as the maximum allowed value (25 µg P/L) (Figure 6). The one with the highest levels is the Santa Lucía River Basin. This river supplies drinking water to the city of Montevideo and its surroundings. So, different plans have been implemented to improve the water quality in recent years. This partly explains the decrease in TP registered in 2019. TP also decreased in the Merín Lagoon Basin (15.7 %), the Negro River Basin (26.5%) and the Uruguay River Basin (45.3%) (Figure 6). However, PT increased in the Negro River in the last two years, which is in agreement with the results of the study carried out by Aubriot et al. (2020) in its reservoirs. They show that in the Uruguay River reservoir TP ranged significantly lower than in the Negro River reservoirs in 2019. It should be remembered that the Negro Basin was the only one where the area sown with summer crops increased during the last three years, unlike the rest of the country where this area decreased (Figure 3B). However, approximately 80% of the area sown with GM crops is still located in the Uruguay River and Santa Lucia River basins (Figure 3B), where precisely the highest TP annual averages have been recorded (Figure 6).

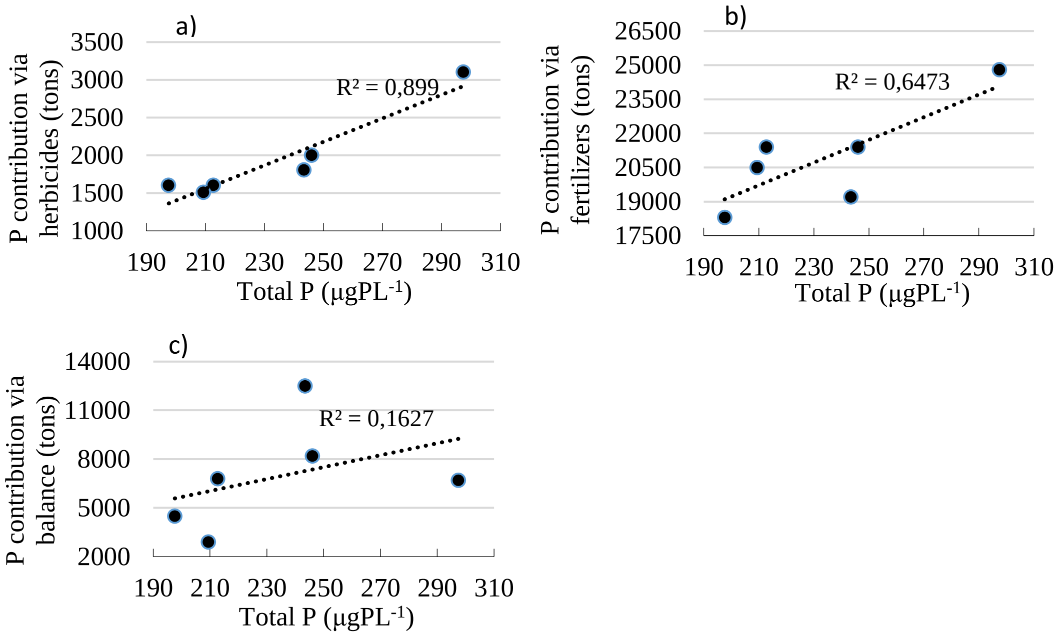
Figure 6. Annual average concentration of total P in four basins: Uruguay River Basin, Santa Lucía River Basin, Negro River Basin, and Merín Lagoon Basin, and their average (µg PL^{-1}).



The annual TP average is compared with P contributions via herbicides, via fertilizers, and via the difference between the P supplied by fertilizers and that extracted in grains (balance). It is observed that the greatest correlation is with P contribution via herbicides (Figure 7.a). This relationship is strong ($r = 0.95$; $p = 0.004$), and statistically significant because the minimum number of data required for statistical strength is 5.

The TP correlation with P contribution via fertilizers is significant ($r = 0.80$; $p = 0.053$) (Figure 7.b), and via balance is weak ($r = 0.40$; $p = 0.43$) (Figure 7.c), but none of them has statistical strength due to the small amount of data. The minimum amount of data required for statistical strength is 10 and 7, respectively. Consequently, significant correlations might not be detected in both relationships, even though they exist.

Figure 7. Relationship between total P (µgPL^{-1}) with: a) P contribution via herbicides (ton), b) contribution via fertilizers (tons), and c) contribution via difference between fertilizers and extraction in grains (balance) (ton).



It should be noted that the competition between phosphate and phosphonates for the same adsorption sites may desorb phosphonates when the relation phosphate/phosphonates increases (da Cruz et al., 2007; Dion et al., 2001). That is the case observed in this study. The contribution of P via fertilizers increased (Figure 4), that is, phosphate increased, and at the same time the contribution of P from herbicides decreased (Figure 5), that is, phosphonates decreased. So, it is possible for herbicides to reach surface waters where they can be biodegraded.

On the other hand, the relationship of TP with the contribution via fertilizers (Figure 7.b) suggests that there is a saturation of the soil's capacity to retain consequent applications of P, as was pointed out by some researchers (Gimsing et al., 2004; Munira et al., 2018). Furthermore, it is also possible that the weak relationship between TP and the balance (Figure 7.c) is indicating that the grains are not extracting P supplied by fertilizers, but rather P that exists naturally in the soil. That entails a nutritional soil impoverishment with the consequent decrease in its fertility.

We must recognize several limitations of the present study. First, there are not available data of the sown area in each basin. Second, we do not have information on how many fertilizers and herbicides are used, either at the farmer or basin level. Third, there are no records of glyphosate or glufosinate-ammonium concentrations in the different basins. Fourth, TP series are short, and some of them do no cover the entire basins. However, we can point out that the balance between the P that enters the soil through fertilizers and the one that leaves in the grains is not enough to understand how the production and management of GM crops contribute to water contamination. P contribution from herbicides has to be incorporated. The quantities applied are of such magnitude that, regardless of their means of transportation, they have to reach the water bodies. In a scenario of vast cultivated areas with GM events resistant to herbicides, it is urgent to formulate strategies and design policies to reduce the environmental externalities involved in this agricultural development. To this end, Uruguay should strengthen national capacities for data collection and systematization of information, and propagate it through a system easy to understand by users.

5 CONCLUSIONS

The growing trend in the area sown with soybeans and maize is associated with the increase in events resistant to herbicides, but fundamentally resistant to glyphosate + glufosinate-ammonium. Due to the increase in production, mainly based on high crop yields and agricultural intensification, the P extracted in an annual grain harvest increased more than the P input via fertilizers. However, the balance is positive. At the same time, the estimated P contribution via glyphosate decreased, and the estimated P contribution via glufosinate-ammonium increased. But, due to the difference in scale in the consumption of herbicides, the TP contribution from phosphonates decreased. On the other hand, the relationship between TP and P via herbicides is robust and statistically significant. The relationship between TP and P contribution via the difference between fertilizers and extraction in grains (balance) is weak, and the relationship between TP and P via fertilizers is significant although they have no statistical power. Yet, it is very likely that with a higher N they could be significant. Therefore, it is feasible to think that herbicides are contributing, directly or indirectly, to increase P contributions to aquatic systems. For these reasons, herbicides should be incorporated into the possible causes of eutrophication.

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