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"Transgenic treadmill": Responses to the emergence and spread of glyphosate-resistant johnsongrass in Argentina

Rosa Binimelis [a,*], Walter Pengue [b], Iliana Monterroso [c]

[a] Institute of Environmental Science and Technology, Autonomous University of Barcelona, 08193 Bellaterra (Barcelona), Spain
[b] Grupo de Ecología del Paisaje y Medio Ambiente, Universidad de Buenos Aires, Argentina
[c] Área de Medio Ambiente, Recursos Naturales y Desarrollo Rural, FLACSO, Guatemala

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ABSTRACT

The broad-spectrum herbicide glyphosate has become the largest-selling crop-protection product worldwide. The increased use of glyphosate is associated with the appearance of a growing number of tolerant or resistant weeds, with socio-environmental consequences apart from the loss of productivity. In 2002, a glyphosate-resistant biotype of johnsongrass (*Sorghum halepense* (L.)) appeared in Argentina and now covers at least 10,000 ha. This paper analyzes the driving forces behind the emergence and spread of this weed and also examines management responses and their implications.

Preventive strategies against glyphosate-resistant johnsongrass fail because of the institutional setting. Reactive measures, however, transfer the risks to the society and the environment through the introduction of novel genetically modified crops that allow the use of yet more herbicide. This in turn reinforces the emergence of herbicide-resistant weeds, constituting a new phenomenon of intensification, the "transgenic treadmill".

1. Introduction

The use of the broad-spectrum herbicide glyphosate began in the 1970s. Since then it has grown steadily to become the largest-selling single crop-protection product worldwide. Over the last years, several factors have contributed to the increased agricultural use of glyphosate: price reductions, an increase in supply associated with patent expiration, further implementation of minimum and non-tillage practices,[1] and the adoption of genetically modified (GM) glyphosate-resistant (GR) cultivars (Woodburn, 2000).

The increased use of glyphosate has led to the appearance of tolerant or resistant weeds which, in turn, implies environmental and monetary costs beside productivity losses (Service, 2007). Although glyphosate was initially considered a low-risk for the development of herbicide-resistance by industrial scientists (Bradshaw et al., 1997), the first records of GR-weeds date from 1996 in Australia. Currently, 14 GR weeds have been documented worldwide (Heap, 2007; Valverde, 2007; Powles, 2008). This article deals with a highly invasive weed called johnsongrass. Several cases of GR johnsongrass have appeared in Argentina while two others have been reported by the University of Arkansas, the Mississippi State University and Monsanto in the USA (Monsanto, 2008). In Argentina, additionally, some common weeds such as *Parietaria debilis, Petunia axilaris, Verbena litoralis, Verbena bonariensis, Hybanthus parviflorus, Iresine diffusa, Commelina erecta* and *Ipomoea* sp. have been reported to be glyphosate-tolerant (Papa, 2000).

The appearance of herbicide-resistant weeds associated with an increased consumption of glyphosate by GR cropping systems has become one of the main ecological risks when releasing GMOs to the environment (Altieri, 2005; Barton and Dracup, 2000; Ervin et al., 2003; Martínez-Ghersa et al., 2003; McAfee, 2003; Powles, 2003; Snow et al., 2005; Steinbrecher, 2001). Until today, those documented cases have been solely assessed from an agronomic perspective rather than accounting for a broader context (Beckie, 2006; Duke and Powles, 2008; Powles, 2008). In this paper we will review and discuss the emergence of GR johnsongrass (*Sorghum halepense* (L.)) biotypes in Argentina and their associated management strategies by means of analysing the political, economic and institutional driving forces leading to this phenomenon. We also devote part of the paper to analysing the consequences for rural dynamics.

In Argentina, over 16 million hectares are dedicated to GM glyphosate-resistant soybean production. Johnsongrass is a cosmopolitan perennial grass native to the Mediterranean region, and considered as one of the 10 worst weeds in the world (FAO, 2007). It was introduced in Argentina in the beginning of the

* Corresponding author.
E-mail address: rosa.binimelis@gmx.net (R. Binimelis).

[1] Non-tillage practices belong to agronomic conservation systems in which the crop is sown over the stubble of the former crop. The soil is not turned over and worked with the minimum movement possible. The system facilitates erosion reduction and higher production under continuous agriculture.

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20th century as forage but by 1936 it was already banned for agricultural purposes. However, due to its highly invasive nature, it continued spreading and became a key restrictive factor for agricultural production. The technological package associated with Roundup Ready soybeans was believed to control the pest by the mid 1990s. However, Monsanto's technicians just recently reported a GR johnsongrass biotype (Heap, 2007). Although the first plots with GR johnsongrass appeared in the north of Argentina only in 2002, it can now be found practically in every agricultural region of the country.

The appearance of GR johnsongrass can be linked to some of the main risk factors associated to the evolution of herbicide-resistant weeds discussed in the weed-resistant management literature. Some of these risks arise from the frequent application of highly effective herbicides, such as glyphosate, in intensive low-diversity cropping systems, and the presence of annual weed species occurring at high population densities and characterised by a wide distribution, large genetic variability, prolific seed production and efficient dissemination (Powles, 2003; Beckie, 2006).

We argue that the political economy of agrarian modernization and biotechnology, and the economics of bioinvasions can offer additional insights for understanding the mechanisms of herbicide-resistant weed's appearance and spread. Agricultural biotechnology has posed new and cumulative challenges to the future of rural spaces (Bridge et al., 2003; Gibbs et al., 2008; Marsden, 2008). Controversies regarding GMOs reflect a clash between agricultural paradigms and development alternatives (Altieri, 2005; Binimelis, 2008; Levidow and Boschert, 2008; Herrick, 2005; Lyons and Lawrence, 1999; Lyson, 2002; Marsden, 2008; McAfee, 2003, 2008; Verhoog, 2007). These controversies intensify previous differences dating at least to the Green Revolution and its social and environmental consequences (Buttel and Barker, 1985; Buttel et al., 1985).

The literature indicates that the diffusion of GM technology took place under the three neo-liberal pillars of privatization, commoditisation and deregulation (Kloppenburg, 1988; Lyson, 2002; McAfee, 2003; Roff, 2008; Salleh, 2006). As we will argue later on this paper, GM techniques became the cornerstone for the development of the agro-industrial model that dominates Argentinean agriculture. The use of glyphosate allowed the use of non-tillage practices, in which the crop is sown over the stubble of the former crop, facilitating erosion reduction and higher production under continuous agriculture. In this way, biotechnology provided a tool for dealing with technical problems arising from large-scale intensive-capital monoculture (e.g. weed management) (Marsden, 2008). This has fuelled the expansion, integration and internationalization of soybean production and commercialisation, which are main aspects of the Argentinean agrarian model, to the detriment of other alternatives (Pengue, 2005). It was during the recent soybean export-tax conflict in Argentina in 2008 that the clash between viewpoints regarding the country's relative position in the world's economy and its bet for trade liberalisation and export competition became more evident. The decline in the price of soybeans in late 2008 because of the world economic crisis will presumably lead to a questioning of the model of export-led growth.

In general, the neo-liberal approach to agriculture relies on a faith in nominally "free" markets to determine agrarian dynamics. An essential feature of this policy prescription is devolution of decisions to the individual sphere (Binimelis, 2008; Cocklin et al., 2008; Devos et al., 2008), and by setting self-interested free choice as the only way of safeguarding rights and liberties (Roff, 2008). The same reasoning operates regarding weed management resistance. However, the social consequences from the application of this approach to weed resistance management have been largely under-explored. Two approaches represent the different attitudes for managing weed resistance (Mueller et al., 2005). These two strategies are also known as mitigation and adaptation, respectively (Perrings, 2005). The first one is identified with proactive or preventive management, and includes identifying major pathways and changing environmental conditions to reduce the likelihood of future resistance, e.g. diversifying the agroecosystem, rotating crops and/or herbicides with different sites of action, or including integrated weed management strategies. The other approach is known as reactive management, and implies actions which aim at reducing resistance costs by changing the herbicide when it no longer works.

As a result, there is a policy dilemma about which approach to choose for managing weed resistance. The choice depends on the stage of the process when the decision is being made but also on the predictability of the resistance and society's attitude towards uncertainty. Although a preventive strategy is usually advised (for the case of glyphosate, see e.g. Powles, 2003, 2008), farmers engaged in high-input systems are reluctant to opt for it because of short-term commercial costs and/or the inability to foresee the economic risks (Shaner, 1995). The reactive approach assumes that novel strategies will become available when required, but also that the costs of these future strategies will not be larger than those of the present management practices. In fact, the evolution of weed herbicide resistance has neither decreased herbicide use nor increased non-chemical practices (Beckie, 2006), but rather intensified herbicide consumption – the so-called "herbicide treadmill". The examination of this tension between preventive and reactive approaches for explaining attitudes towards herbicide-resistant weeds comprises a major drive for this study.

The aim of this paper is to analyze both the driving forces behind the initial spread of GR johnsongrass and the social, economic and environmental implications of pre-emptive or reactive response strategies. It also discusses reasons behind farmers' willingness or reluctance to adopt preventive resistance management strategies, as well as institutional conditions and constraints. The existence of a new form of treadmill phenomenon, not only leading to the increase of herbicide use but also to the intensification in the use of GM crops, will also be explored.

This paper is structured in five sections. Following the introduction and methods, we discuss the driving forces behind the appearance of GR johnsongrass. The Argentinean agricultural system is characterized, with special focus on the GR soybean production and future scenarios. Next, we describe the environmental history of johnsongrass and the emergence of GR biotypes in terms of spread, potential impacts and responses put in place. Finally, we discuss the implications of different management strategies and provide some concluding remarks.

2. Methods

There is a small but hitherto undisputed body of evidence concerning the existence of the invasion process of GR johnsongrass (Heap, 2007; Powles, 2008). In this study, we present the results of qualitative field research on actors' perceptions and understanding of the process. The qualitative techniques included semi-structured group and individual in-depth interviews as well as participatory observation.

The use of these techniques is grounded in the characteristics of the case study. Complexity inherent to the invasion process and to the production system is reflected in uncertainties concerning the impacts of GR johnsongrass spread. Data regarding the degree of spread of GR johnsongrass are incomplete due to lack of official statistics and voluntary reporting (as will be discussed in following sections). This rules out the analysis of impacts from a quantitative perspective. At the same time, there are different perspectives regarding the significance of the invasion, which are better elicited through qualitative approaches (Kvale, 1996).

The informants were selected among main actors who participate in the management strategies and/or governance of the issue of GR johnsongrass. During 2007, 20 semi-structured interviews were conducted in the provinces of Salta, Tucumán, Santiago del Estero, Entre Rios and Buenos Aires. These interviews aimed at eliciting the viewpoints of experts, practitioners and actors involved in the GR johnsongrass conflict. Interviews were conducted with three botanists specialized in weeds, three affected farmers, two ecologists, two representatives of the main biotechnology company in Argentina, three agrarian technicians, one representative of the National Agrifood Health and Quality Service (SENASA), four scholars and researchers at private agronomy institutions and two representatives of producers' associations. The selection of actors was based on the different roles and perceptions related to the management of the GR johnsongrass (Flick, 2006; Bauer and Gaskell, 2000). The interview guide included four main aspects: (a) agricultural transformations and productive dynamics on the study area; (b) driving forces behind the emergence of GR johnsongrass; (c) an assessment of the costs and impacts derived from the appearance of the GR johnsongrass; and (d) an estimation of the GR management measures and proposals. Collected information was analyzed using ATLAS.ti, a qualitative data analysis software which handles large data sets by setting categories, systematising and refining concepts (Kelle, 2000; Lewins and Silver, 2007).

Information on the socio-economic and biological processes was collected to unravel the environmental history of the johnsongrass, the Argentinean GR soybean system and the current implications of the agronomic production model. A literature review emphasizing the political economy of biotechnologies and the economics of bioinvasions and weed management, as well as general insights from ecological economics and agroecology provided the analytical tools for tackling the GR johnsongrass conflict.

3. The Argentinean GR soybean system

The driving forces behind the appearance of GR johnsongrass cannot be separated from Argentina's rural development model, particularly the institutional setting and the new agrarian organization of space (i.e. the *agriculturisation* and *pampeanisation* processes, as discussed below). Seen this way, the emergence of GR johnsongrass could be interpreted as a foreseeable "side-effect" of these processes, and responses to it would be determined by the system's constraints and opportunities as well as by the future productive scenarios.

3.1. Production system and technological applications

Modern Argentinean agriculture started in the late 19th century with a mixed production system (based in cattle ranching and agricultural crop rotations) which promoted an extensive low-input agronomic cropping scheme in the *Pampas* (Viglizzo et al., 2002). The *Pampas* is a vast, flat pastureland of Argentina, which covers more than 55 million hectares of arable land. Over the years, cultivation with inappropriate tillage systems and machinery has lead to erosion. In the early 1990s, the adoption of no-till practices diminished the erosion problems but raised herbicide consumption. Non-tillage systems and soybean–wheat rotation displaced the mixed crop-cattle production system in most of the *Pampas* pastures, allowing farmers to produce three crops over a two years period. These practices also opened a window of opportunity to a range of herbicides with different modes of action in each stage of the soybean cultivation system. As a result, weed control became 40% of the input costs for farmers. By 1987, 50 chemical compounds were marketed for weed control, 22 of them for soybean fields, under several different formulations. However, only four principals comprised 60% of the market value (León et al., 1987). Fifteen companies controlled the market; of which 80% were multinational enterprises (Pengue, 2000).

These new technologies accompanied the rise of permanent agriculture, which displaced traditional cattle production to marginal areas or feedlots. The process of *agriculturisation*, as it is known in Argentina (Manuel-Navarrete et al., 2005), transfigured the mixed farming system towards an agri-industrial model. It is characterised by the diffusion of specialised mono-cultural crops, the progressive intensification of the system by the use of external inputs, the geographical separation of livestock and crops and a growing reliance upon public, but also increasingly private, research and extension system (Marsden, 2008).

In the extra-*pampean* areas, which are characterized by more complex environments, the system gives rise to a greater reliance on external inputs for weed and pest control. The process, called *pampeanisation*, entails the export of the technological, financial and agronomical model of the *Pampas* to other ecoregions, such as the Great Chaco or the Yungas (Pengue, 2005), thereby expanding the agricultural frontier. Statistically, this trend is evident in the demand for new farmland, which has pushed Argentina's deforestation rates to 0.85% per year, above those found in Africa (0.78%) and above the average in South America (0.50%) (Morello and Pengue, 2007). The Department of Agriculture, Cattle Ranching, Fisheries and Food (SAGPyA, acronym in Spanish) documents a threefold increase in the rate of soybean expansion between 1996/1997 and 2006/2007 sowing seasons.

The processes of *agriculturalisation* and *pampeanisation* were fostered by the introduction of the mono-cultural GR transgenic soybean model under no-tillage practices in the mid 1990s. Using glyphosate, farmers were able to control a diversity of weeds (including the most conspicuous, e.g. *Sorghum halepense, Cynodon dactylon, Cyperus rotundus* and *Chenopodium album*) at a very low cost. This allowed farmers to manage more land and increase overall productivity and profitability based on a vertical integration model (Mueller et al., 2005). In the 2006/7 campaign, 16 million hectares were sown with soy, and production reached its historical record: 48 million tonnes, half of the total agricultural production for Argentina (SAGPyA, 2007). Practically 100% of total soybean production is based on genetically modified GR soybeans.

3.2. The institutional setting

A series of structural reforms were necessary to allow a rapid diffusion of GM technology. Government policies were among the major driving forces transforming extensive agriculture and cattle raising to fit the requirements of international markets.

The shift in Argentinean agriculture towards *commoditisation* (including an emphasis on export production) produced a substantial surplus in the current account balance, allowing payment of interest on external debt, while increasing economic resources to maintain social plans. Exports account for most of the improvement in tax revenues and half of these taxes come from soybeans exports and its derivates (Damill et al., 2006). At the same time, empowered market forces had a stronger voice in strategic production decisions. Responsibilities were transferred from the state to technical NGOs and agribusiness corporations, while services such as extension usually offered by state institutions were dismantled (Manuel-Navarrete et al., 2005). As a result, agricultural modernization processes and the adoption of GM technologies occurred mostly in the absence of state actors and institutions. This implied an important shift in actors concerning agrarian dynamics, development pathways and technological modernization. The active role that private entities played in technological diffusion and professional assistance is evidenced in strategies that are based on private sector responses. Multinational corporations become central actors and the major vehicle of technological modernization (Spielman, 2007).

3.3. The new social organization of space

Linked to the institutional setting, the social organization of space plays a major role as a driver in the emergence and spread of the GR johnsongrass as well as in the adoption of response strategies. Changes in spatial patterns of land use associated with the expansion of soybean in Argentina have been explored in detail elsewhere (Paruelo and Oesterheld, 2004). These spatial transformations associated with changes in land tenure structure are particularly relevant for the analysis of johnsongrass spread. According to the last agricultural census, units larger than 10,000 ha have increased 13% in number and 14% in extent in *Pampas* between 1988 and 2002 (SAGPyA, 2003). Since the 1990s, there has been also an increase in agricultural land concentration in the Northern provinces of Argentina, primarily as a function of soybean production. In the Northern provinces of Salta and Santiago del Estero between 1988 and 2002 the area devoted to agriculture increased by 70%, which means an expansion of 120,000 ha per year of the agricultural frontier. About 66% of this increase is explained by increments of soybean-cultivated areas (Paruelo and Oesterheld, 2004).

New forms of land tenure favour an increasing concentration of agricultural production and management. Informants report that renting land through leasing arrangements and other financial mechanisms has now come to be an economically efficient option, a development that coincides with Kloppenburg and Geisler's (1985) analysis of the agricultural ladder in the United States. Their findings confirm that new social forms of production are no longer linked to the productive chain through ownership, but rather the system has broader objectives of net revenue and economic efficiency. In Argentina, more than 50% of the cultivated land is leased and, according to Pengue (2005), 75% of the grain in the *Pampas* is produced by large land leaseholders. Most of the leasing contracts are annual, which impose a high pressure on the land in order to obtain the maximum revenue in the shortest time. Production and management concentration facilitates the adoption of input-oriented (machinery, fertilizers, pesticides, GR soybean) and process-oriented (no-tillage) systems. However, technological adoption and change are closely related to capital and information availability. While changes in production practices and adoption of GM technologies favour yield increases, Paruelo and Oesterheld (2004) have documented that beneficiaries of technological improvements are mainly large producers. For this reason, the extension of the lease regimes up to 5 years has become one of the main demands of small and medium-sized farmers (Federación Agraria, 2008).

In the case of soybean production systems, production processes are dominated by managerial tasks performed by a contractor (Manuel-Navarrete et al., 2005) representing either national corporate or international investment interests. According to Buzzi (quoted in Pengue (2007)) 3% of the producers are responsible for 70% of the soybean production. Much of this production occurs under the auspices of the so-called "sowing pools". The sowing pool comprises a financial mechanism for soybean production which brings together a landowner, a contractor and a technician in a novel form of agricultural enterprise. The sowing pools favour agrarian capital concentration in the hands of large company contractors that lease the land from small and medium landholders.

3.4. Future scenarios of the production system

In this section, we analyze major recent trends in Argentina's agricultural production system. Besides soybean seed and flour feeding the ever increasing international meat market, Argentina is also one of the greatest exporters of vegetable-oil in general and of soybean and sunflower derivatives in particular. It is considered to have some of the most efficient and technologically advanced milling equipment for vegetable-oil in the world, producing more than 154,000 tonnes per day. Strategic geographical location of the milling infrastructures at big harbours facilitates the export of 95% of this oil production (Lamers, 2006; Pengue, 2006). The sector is characterised by an industrial oligopoly, as 85% of the installed milling potential is processed by six companies.

Because of this capacity, Argentina is potentially a prime supplier for the growing biofuel industry, both for biodiesel (the raw material of which is vegetable oil from soybeans, sunflowers or canola) or bioethanol (derived from alcohols obtained from maize or sugarcane). For instance, the EU goal of 5.75% biofuel blending by 2010 would require a fivefold increase in EU production, posing a great demand for imported raw materials (APPA, 2007; Dufey, 2006; Russi, 2008). Future projections foresee biofuel production taking place mostly in developing countries, with cheap land and labour and where climatic conditions are more favourable (Wicke, 2006).

Moreover, with internal demand likely to increase due to the Argentinean "Biofuels Act" (Law 26.093) requiring 5% biodiesel content in petroleum derivates by 2010, domestic demand is estimated to reach 600,000 tonnes/year for biodiesel. At the present production rates, it is calculated that 7.3% of the soybean surface is needed for supplying this annual target of production in the first year of implementation (3.5 million tonnes of soy beans). Therefore, Argentina could not become diesel self-sufficient through soybean-derived biodiesel unless the cultivation surface is significantly increased. Although Argentinean authorities remain confident of the opportunities to increase soy yields, most of the large soybean growers, including Argentina, the USA and Brazil, have seemingly already optimized their production, as they have experienced little growth in last years (Johnston, 2006). International demand could press further for the expansion of the agricultural frontier. In the case of ethanol, Argentina is also one of the world's lowest cost producers of maize. Domestic demand is estimated at around 160,000 tonnes/year for bioethanol.

4. "With the GR soybean we arrived in paradise...but it was so short-lived...: the emergence, impacts and responses to GR johnsongrass

4.1. Environmental history of johnsongrass management in Argentina

Johnsongrass was introduced in Argentina at the beginning of the 20th century. Although it was already considered strongly invasive, the Ministry of Agriculture proposed it as a high-yield forage suitable for poor soil conditions (Estrada, 1907; Vallejo, 1913). Agronomists in Tucumán (north of Argentina) were soon alerted by its rapid, invasive potential and recommended its prohibition (Cross, 1926, 1927). By this time, land abandonment, decrease of land prices and high productivity losses in the weed's wake were also documented (Schultz, 1931), which led to describing the johnsongrass invasion as "the farmers' terror" (Cross, 1934a). In 1930 it was considered a pest for agriculture in the humid and semiarid regions of the country. Although international sales and imports of johnsongrass seeds and rhizomes were forbidden (de Rocha, 1930), domestic trade was not halted (Cross, 1934b). Only in 1951 were sowing and breeding banned at the national level.

Despite these policies, by the early 1980s some estimates assert that 6 million hectares of the rolling *pampas* were infested (Leguizamón, 1983), while other estimates are as high as 15 million hectares, with over 94,000 affected producers (Ladelfa et al., 1983). Until the 1970s, control techniques were either mechanical or manual, and cultivars coexisted with a wide, polyspecific weed population. In the 1970s, a series of herbicides (e.g. MSMA or Trifluralina) were introduced in the Argentinean market, and johnsongrass control techniques combined mechanical and chemical strategies. By 1977 the so-called "Plan Piloto de Salto" was launched by the National Institute of Stockbreeding Technology (INTA) in the province of Buenos Aires. Its main objective was to progressively recuperate the infested fields through implementing management techniques based on rotation practices, the use of winter cover crops and mechanical and/or chemical measures (Rossi and Cascardo, 1981). A series of empirical field trials were conducted to evaluate the efficiency of these techniques, and to improve background knowledge on the dynamics of johnsongrass (e.g. reproduction patterns, susceptibility to the temperature or to fertilisation). Costs of different management alternatives over three-year rotation periods varied between 20% and 45% of the total production costs (Cascardo and Rossi, 1979). At that time, MSMA, Dalapon, Pirifenop and glyphosate were recommended (Barletta et al., 1977). In the 1980s, the range and use of herbicides increased, both for pre-sowing herbicides and grass-specific graminicides.

The subsequent introduction of GR soybeans and the constant use of glyphosate apparently succeeded in controlling the weed. As one informant reported: "glyphosate becomes the essential tool for fallow-land and soybean cultivation in 1996. Johnsongrass practically disappeared from the rolling *Pampas*, except from patches on uncultivated land... but none in agricultural land".

The illusion of infallibility of glyphosate to control weed species shifted emphasis toward chemical control at the expense of integrated weed management[2] and the weed control experts groups. The soybean herbicide market was contracted. As one engineer stated in an interview: "Traditional products reduced their market presence. It is difficult to get any other product. Everything except glyphosate has to be ordered". Others have noted that the rate of innovation in developing new herbicides has declined as agrochemical companies have acquired seed companies to produce herbicide-resistant crops. Moreover, farmers' willingness to use other alternatives or explore weed thresholds has been reduced after GR crops adoption (Martínez-Ghersa et al., 2003; Rüegg et al., 2007). When surveying Argentinean farmers, White (1997) found that among the main motivations for adopting GR technology were better and more simplified weed control in the short term in addition to a decreased expenditure in herbicides, labour and fuel.

The adoption of herbicide technology in the 1960s, and glyphosate later, has been accompanied by conceptual changes in the definition of weeds and their role within the production system. For some actors, weeds may be considered an intrinsic limiting factor in the *agriculturisation* process, the economic impact of which must be minimised; while for others they are an "enemy" to be defeated in the ongoing effort to dominate nature. Among frequently used terms in weed management are "control", "eradication", "fight", "defeat", "wipe out", "weapon" and the use of medical metaphors and hygienic terms such as "clean" to refer to a chemically sterilized field. All these were identified in the interviews and are examples of the second mindset described above.

Glyphosate consumption became the centre of the weed management strategy, increasing sharply from 1 million litres in 1991 to 180 million in 2007. Although glyphosate is considered a low environmental risk herbicide by some authors (Duke, 2005; Duke and Powles, 2008), those with an eye on the bigger picture have warned that "the substitution of traditional crops [in Argentina] by GR soy in the past decades represents a large scale, unplanned, ecological experiment, whose consequences for natural ecosystems, and aquatic environments in particular, are poorly understood" (Pérez et al., 2007; see also Altieri (2004), Casabé et al. (2007), Relyea (2005)).[3]

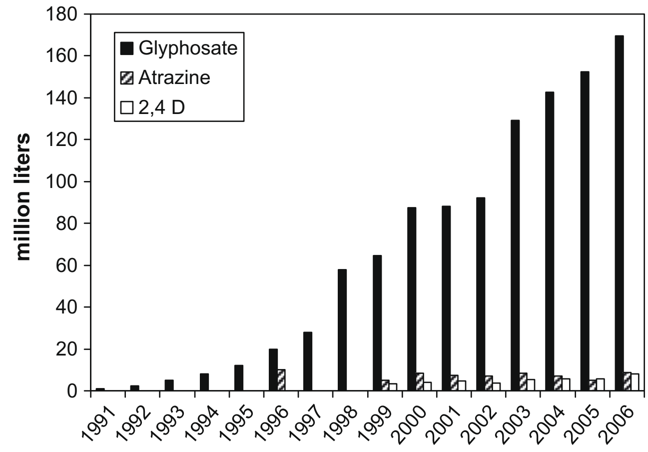

Fig. 1. Evolution in glyphosate, atrazine and 2,4-D consumption in Argentina, 1996–2006. *Source:* Statistics have been compiled from Pengue (2000) and CASAFE (Cámara de Sanidad y Fertilizantes de la República Argentina (2007)).

Initially after the adoption of GM soybeans the increased use of glyphosate was accompanied by a decrease in the consumption of other herbicides such as atrazine or 2,4-D. However, during the last growing seasons, the consumption of these herbicides has risen again (see Fig. 1). These results coincide with those of Bonny (2008), who concludes after assessing soybean cropping in US that the total amount of herbicides applied per ha decreased initially between 1996 and 2001, but tended to rise afterwards.

4.2. The emergence of GR johnsongrass biotypes in Argentina

Farmers from the province of Salta, northern Argentina, detected the appearance of a GR johnsongrass biotype in 2002. Samples were taken and brought to the USA by Monsanto in 2003. However resistance was only reported indirectly to the National Agrifood Health and Quality Service (SENASA) during a congress presentation offered by Monsanto in December 2005 (Passalacqua, 2007). The Tucumán University then confirmed it in the same year. It is possible that this delay has been critical for the future spread of GR johnsongrass. An affected producer commented on the time lag between early detection and confirmation: "We warned Monsanto and they came. But we were losing time, nearly two years passed [...] The message from all scientists at that moment, not only Monsanto's, was that it was practically impossible to acquire resistance to glyphosate due to its site of action. Now it has changed". At that time, different authors already warned of the potentially intense selection pressure for weed resistance by genetically modified herbicide-resistant crops. This would in turn jeopardize the future use of glyphosate (Owen and Zelaya, 2005; Powles, 2003; Reddy, 2001; Shaner, 2000; Snow et al., 2005; Tiedje et al., 1989; Wolfenbarger and Phifer, 2000). By 2006, eight GR weeds were already confirmed worldwide; three cases were associated with the use of herbicide-resistant crops (Cerdeira and Duke, 2006).

[2] The aim of integrated weed management (IWM) is to use of a combination of different practices to maintain weed densities at manageable levels. Methods include cultural practices, use of biological, physical, and genetic control agents, and the selective use of herbicides. For more on IWM see Buhler et al. (2000), Mueller-Schaerer (2002).

[3] For a discussion on human health impacts derived from glyphosate utilization in Argentina refer to Bradford (2004).

Although the first cases emerged in the Salta province (Valverde and Gressel, 2006), GR johnsongrass was reported in 2007 in all agroproductive provinces in northern Argentina and also in some central provinces, such as Santa Fe. It is estimated that the affected area in the north of Argentina covers 10,000 ha (Passalacqua, 2007), and our informants expected that the potential affected area might reach 100,000 ha. Fig. 2 shows the areas where GR johnsongrass' has been reported.

4.3. Potential impacts associated with GR johnsongrass

Involved actors offered different analyses of the recent appearance and spread of GR johnsongrass in Argentina and of its implications. They discussed the similarity of most of these impacts to those already encountered in the 1930s. Again, increases in the control costs were reported in the affected fields. Some informants focused on farmers' capability to adapt to the new conditions: "This will weed out producers. Those who are attentive will succeed; those who clean their machinery, etc... will have everything under control. The problem is with those who are still confident about managing with glyphosate. They will have problems. Other types of resistance will occur. This is the big topic." A major challenge is replacing an extremely simple weed management, based on a "fantastic technology that makes Argentina competitive worldwide" (interview, agronomist), with a more complex integrated weed management system.

Yield loss and incremental control costs have induced changes in the lease regime (both in the price and length of the contract), as a consequence of the depreciation of the value of affected lands. Some stakeholders have also discussed the increase in the control costs as an added driver for the need to scale-up the economic activity, which will cause the abandonment of small and medium-sized farms or further push the agricultural frontier in order to maintain the margin of benefits. The process is similar to the one discussed by Kloppenburg (1988, p. 35) regarding technology adoption, in which farmers who fail to adapt to new technologies are continuously driven out of business and their operations are absorbed by more successful producers, ensuring a secure and expanding market for the technology supplier.

The implementation of johnsongrass' management measures can be related to a series of socio-economic and environmental impacts. Agronomists in the affected areas suggest control strategies that involve returning to more severely toxic and older herbicidal ingredients such as MSMA, 2,4-D and combinations of these with glyphosate in a new burn-down strategy in the no-tillage GR system, or by using rucksack equipments for a plant by plant control. Economic costs threaten to accrue as practices are prescribed for the containment of GR johnsongrass, such as cleaning of agricultural machinery, or with the potential rise in seeds' costs due to purity standards. The technology advantage found by farmers in the implementation of the GR soybean in terms of cost reduction could be lost. Returning to old herbicides increases control costs drastically, leaving middle-sized farms in a precarious situation. The increased use of MSMA or 2,4-D, with higher potential environmental and health impacts than glyphosate, or the promotion and introduction of genetically modified seeds resistant to other herbicides, will be discussed in next section.

4.4. Management responses to GR johnsongrass

Management strategies can be divided into proactive or reactive, though options may be limited depending on how advanced the invasion is at the decision-point. We will now review the different classes of responses and their implementation in Argentina (see Table 1). It is worth mentioning that the main agricultural extension agents in charge of farmers' assessment, especially in the north of Argentina, are agronomic engineers representing private, mixed companies or private NGOs such as ProGrano (Northern Grain Producers Association) or AAPRESID (Argentinean Association of Non-Tillage Producers).

Preventive measures: In a glyphosate-based production system, preventive measures would involve searching for more diversified production, requiring a sophistication of the system as well as improving management of knowledge and time. Given the

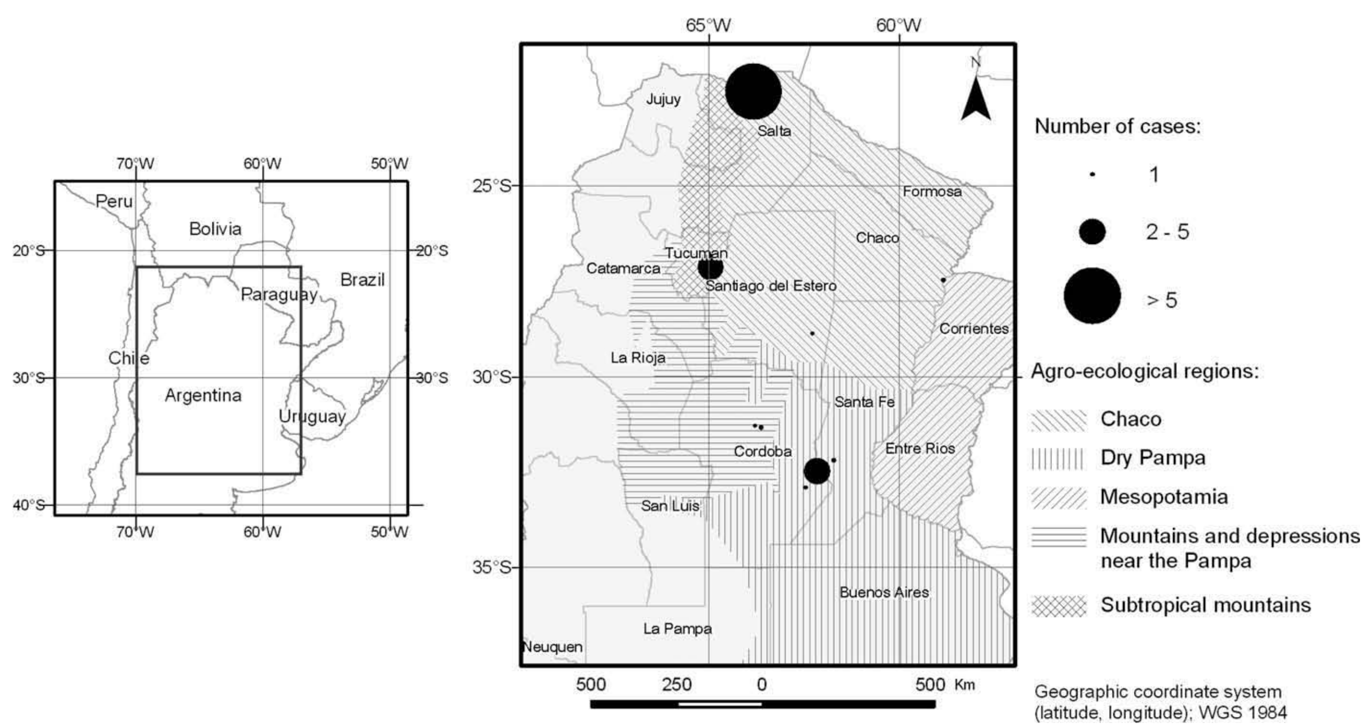

Fig. 2. Areas with confirmed GR johnsongrass in the North and Centre of Argentina (2008).

Table 1
Responses implemented in Argentina for the management of GR johnsongrass.

Before GR johnsongrass emergence	After GR johnsongrass emergence
Prevention	Prevention
–	–
Early detection	Assessment
–	SENASA hires an external consultancy in June 2006 for evaluating the scale of the problem and to propose management recommendations
	A National Advisory Board for Resistant Pests (CONAPRE) was launched in November 2006
	Two workshops were held in September 2006 and June 2007, gathering weed experts, producers and policy-makers
	Early detection
	A communication system for detection of GR johnsongrass was implemented
	Containment
	Informative campaign launched by the Experimental Agroindustrial Station Obispo Colombres and ProGrano in 2007
	Control
	Chemical control has been tested with several herbicides (MSMA, 2,4-D, halaxifop metil, cletodim, as well as graminicides applied locally) in soy fields.

Sources: ASAPROVE (2006), Olea et al. (2007), Passalacqua (2007), SENASA (2007); field work interviews.

predominance of economic and technological optimism, no preventive measures were taken before the emergence of GR johnsongrass, nor in unaffected areas once it had already appeared in other areas of the country.

Reactive measures: Once GR johnsongrass appeared, reactive measures were implemented. These can be divided into assessment, early detection, containment or control measures (GISP, 2007). Eradication has not been discussed as an option by stakeholders.

Assessment can be considered the first step of a management programme. It involves evaluating the different elements within the current situation (extent of the area to be managed, determining the management goal or the stakeholders involved). In 2006, the SENASA hired an external consultancy to assess the state of affairs in Argentina (Valverde and Gressel, 2006). Its main recommendations include measures such as putting in place early detection systems (visual and satellite-based), designing a public information campaign, promoting rotation schemes for avoiding or delaying the appearance of resistance, implementing measures for containment and promoting basic research and investigation on chemical control. Two workshops were held in September 2006 and June 2007 presenting and following-up this assessment, convening weed experts, producers and policy-makers. A National Advisory Board for Resistant Pests (CONAPRE) was launched in November 2006 charged with coordination (SENASA Resolution 470/2007). Its functions are similar those of the first Board against Weeds created in 1936 to manage common johnsongrass.

Early detection: SENASA has put in operation a centralised system for reporting suspected cases of GR johnsongrass. However, there has been a low number of reports. This can be attributed in part to the severity of GR johnsongrass' impact and the uncertainty of the consequences for those who report. It can be illustrated by some excerpts from interviews: "The reports are few because people are afraid of reporting because of getting lower rents and because they do not know how the authority is going to react, because their fields could be closed down,...''; "If a farmer has or detects GR johnsongrass, will he say it? Will he identify the problem in his field? He doesn't know what could happen because legislation is not clear: would the field be closed down? Would production be retained? What would be the cost of machinery for him? Ignorance of legislation can be a limiting factor in confronting the problem [...] While the problem is in the fences, it is everybody's problem, or others' problems; but when the problem is in his field, I do not know how he will react." Additionally, farmers seem to be reluctant to question their trust on technology: "In general there still is [...] some resistance to accepting the problem. I make the comparison with some parents that deny that their son is different. They deny the problem. But it is serious. And what we have detected is that producers are reluctant to report the problem, to say it, to confess it. [...] Probably there are many more cases than the ones we have detected." The resulting lack of data regarding the scale of the problem makes containment difficult.

Containment is aimed to restrict the spread of GR johnsongrass and to enclose the population in a defined geographical range. Again, early detection and monitoring will be a critical feature. In 2007 the Experimental Agroindustrial Station Obispo Colombres launched an information campaign through radio and TV spots, newspapers and posters focused on procedures for avoiding dispersion, especially those related to hygienic measures for machinery (agricultural engineer, interview). The Agroindustrial Station is a joint public–private venture.

Control measures: Much of the effort has been directed to control measures. The objective of these is to reduce the density and abundance of GR johnsongrass below a pre-set acceptable threshold. Control methods are usually classified as mechanical, chemical, biological, habitat management or integrated pest management (GISP, 2007). SENASA, who is the agency in charge of the control policies, has mainly promoted chemical methods. The main herbicide companies lead the research, in coordination with private NGOs (such as PROGRANO) who are in charge of developing the resulting strategies. In the last years, no new herbicides with new modes of action have been introduced in the market and no quick developments are expected (Green et al., 2008). For instance, the last compound with a new mode of action – HPPD herbicide – was commercialized in Europe in 1991 (Rüegg et al., 2007). Therefore, strategies to control GR johnsongrass rely on already commercialized herbicides, either directly or through the development of novel GM crops with new herbicide-resistance characteristics, or on varieties resistant to even higher doses of glyphosate (Service, 2007).

Informants have described trials conducted in Argentina aiming to control GR johnsongrass in soy fields. At the moment, the resistance mechanism is still unknown and therefore research for chemical control is conducted on a trial and error basis. These methods include the use of glyphosate mixed with MSMA, 2,4-D, cletodim or haloxifop, post-emergence graminicides (e.g. Micosulfuron, Imazethapir) or for use in fallow fields (atrazine, paraquat, 2,4-D, metsulfuron metil). They do not fully cover the complete spectrum of weed species treated by glyphosate, and entail higher management costs for the fields. For instance, Muñoz (2006) estimated in 2006 that the cost of controlling GR johnsongrass with a mixture of 2,4-D and glyphosate increases production costs by 19.3% per hectare, apart from increased biological and human health risks. The price of the two herbicides has risen steadily since then. Other authors estimated that controlling a glyphosate resistant weed could double the herbicide expenditure per hectare in Argentina (Tuesca et al., 2007). Moreover, herbicide mixtures can inadvertently accelerate the evolution of multiple resistance if they fail to meet basic criteria for resistance management or are applied repeatedly (Beckie, 2006). However, weed control specialists remain confident: "in spite of complexity, it is possible to face and win the battle on this problem" (interview, weed management expert). Yet their efforts seem to depend on the continued use of glyphosate. On July 2007, a commercial maize variety, stacked with RoundUp resistance (i.e. GR) and Bt was released in Argentina. Rotation with GR sugarcane was also suggested by some companies. Season by season, crop by crop, including fallow fields, glyphosate seems to be the unique alternative.

4.5. Enhancing the market: new developments in the GM scene

Biotech companies have recently launched novel GM crops with new herbicide-resistance as a response to the appearance of GR weeds (Green et al., 2008). For instance, in September 2007 DuPont and Nidera announced the glyphosate and sulfonyureas-resistant soy varieties Finesse-Sts (Ciuci, 2007). In their presentation in Argentina, the representatives of Nidera soy varieties stated: "For growing towards the future, it is necessary to present solutions to new problems, such as tolerance or resistance to glyphosate." DuPont has similarly developed the so-called GAT/HRA technology, which combines glyphosate and ALS resistance (including sulfonylurea and imidazolinone herbicides) for soy and maize along with other crops (Green, 2007). The technology has been commercially applied by Pioneer Hi-Bred and DuPont Crop Protection in the so-called Optimum-GAT trait, with sales anticipated by 2010–2012 (Pioneer, 2007). To date, 95 species have been reported to be ALS-resistant, including johnsongrass (Heap, 2007).

In May 2007 Monsanto and the University of Nebraska also presented Dicamba resistant technology in *Science* magazine, as a strategy to extend the effective lifetime of glyphosate and preserve no-till or reduced-till planting practices (Behrens et al., 2007). The technology could also be applied to soy, tobacco and cotton. Dicamba is a synthetic auxine considered as an herbicide with low toxicity, but with high residuality. It is a selective systemic herbicide for broadleaf weeds. Chemical researchers recommend that Dicamba resistance genes be used "stacked" with glyphosate resistance genes to allow farmers to alternate between the two herbicides or mix them. In the case of glyphosate, whose patent has expired, gene stacking is particularly profitable as it increases the value of the seeds by including two or more technological fees rather than just one (Bonny, 2008). In a study conducted by Peterson and Hulting (2004), Dicamba was found to have higher relative risks than glyphosate for five of the nine ecological receptors evaluated. In an estimation of relative ecological risks of herbicide active ingredients made by Duke and Cerdeira (2005), Dicamba was classified as having 220 more specific risks compared to glyphosate. *Kochia scoparia*, *Stachys arvensis* and *Galeopsis tetrahit* weeds have already been reported as Dicamba-resistant (Heap, 2007). The first two are present in Argentina.

In turn, Dow AgroScience has recently presented its progress in the development of maize and soy varieties resistant to 2,4-D, "fop" grass herbicides and insects (Dow AgroSciences, 2007a). Although offered as a herbicide with few resistant weed populations, resistance to 2,4-D has been registered in 16 weed plant species. First records already date from 1952 (Heap, 2007). The company expects to commercialize GM maize in 2012/3 or 2014 for soybeans.

In maize production, Dow and Monsanto companies have recently presented a genetically modified maize, in which eight genes are stacked for herbicide tolerance and insect-protection. It has been published as the "'all-in-one' answer to demands for a comprehensive yield protection from weed and insect traits" (Dow AgroSciences, 2007b). The new GM crop –SmartStax – is expected to be commercialised in the US by the end of the decade, combining glyphosate and ammonium glufosinate resistance with corn worm protection.

Finally, research has also been conducted to obtain glyphosate-tolerant maize with higher resistance to the herbicide. Athenix Corp, for instance, expects to submit a regulatory package by the end of 2008 in the USA for maize capable of withstanding at least eight times the standard field rate of glyphosate recommended, providing "the highest levels of glyphosate tolerance available" (Athenix Corp., 2007). Field trials for soybean are about to begin.

5. Discussion and concluding remarks

The process of *agriculturalisation* in the rolling *Pampas* that began in the mid 1970s, and the subsequent *pampeanisation* of extra-Pampean regions have meant a strong intensification of the productive system. These processes were enabled by the long-standing representation of Argentina as an "almost unlimited" land (Garavaglia, 1989), metaphorically described as a desert that could be transformed for production through the submission of the environment (Pengue, 2003) and the local populations (Navarro Floria, 1999). Although these material and representational practices started in Argentina long ago, they played a central role in the massive diffusion of soybean production in recent years. At the same time, key roles were played by a series of institutions (e.g. increasing offers of credits for investments in phytosanitary control, especially herbicides during the 1970s (León et al., 1987)) and innovations in land tenure arrangements. With the introduction of the GR technology package, intensification under the efficiency paradigm became the sole productive alternative (Pengue, 2004).

In these processes, weed management was identified as the bottleneck for the production model, and great expenses of capital and labour were devoted to weed control. As the example of johnsongrass illustrates, the "magic bullet" approach was favoured. As discussed by Scott (2005), this term was first coined in biomedicine to refer to a model centred on the agent as the sole cause of disease. Integrated pest management literature argues that the approach has been similarly applied to weed management (Buhler et al., 2000; Hoy, 1998; Neve, 2007; Scott, 2005). Synthetic herbicides are aimed to react once the pest has appeared. However, herbicides are usually employed without analysing ecological and evolutionary dynamics of the site, nor the social conditions of application (ibid). This blind spot has also been discussed in the context of herbicide-resistant GMOs (Altieri, 2005; Altieri and Rosset, 1999; Appleby, 2005; McAfee, 2003; Mueller-Schaerer, 2002).

As a consequence of the approach, every pest becomes a target (Prokopy, 1987). In that sense, weed control has been equated to weed-free, and field appearance becomes then a major motivation for weed control (Jones and Medd, 2000). This preoccupation could also partly explain the increasing glyphosate consumption in Argentina (besides the increment of area sown with soybeans). As a single post-emergence application is insufficient to achieve total weed control, repeated applications are needed. This approach has been metaphorically identified by critics of GM technology as "green concrete", since no other plant, except the crop, can grow (Levidow and Carr, 2007). However, from an economic point of view, the optimum level of weed control may be less than 100% unless if it is assumed that the crop is infinitely valuable or control costs are zero (Martínez-Ghersa et al., 2003).

A 'golden moment' of soybean production gave momentum to the magic bullet approach. The harvest of 2007/2008 broke the historical records for soybean yield and price (in part due to the sharply escalating biofuels demand) giving support to the technological optimism that drives industrial agriculture in Argentina. However, the GR technology may be judged as a technological lock-in, discouraging the adoption of weed-resistance preventive measures and unable to cope with GR weeds. As this case study shows, Argentinean farmers were deskilled at an extraordinary speed, becoming weed ‘‘illiterates” as they forgot early attempts to integrate pest management. In that sense, literature on path dependency points out that dynamic increasing returns imply that, once chosen, a technology path has the tendency to be stretched. Results from our case study coincide with the findings of Cowan and Gunley (1996), who explain this path dependency by the interplay of three factors which determine the low rate of adoption of integrated pest management as an alternative to chemical management: (a) initial low payoff for this technology, as the necessary knowledge is not available; (b) uncertainty on the outcomes; and (c) ‘‘coordination” problems among farmers in terms of the effects that neighbouring practices have on their own fields. All these factors were fostered in this case by ‘‘glyphosate dependence”.

Recommendations generally assume that the management strategy of an individual farmer shapes the future incidence of herbicide-resistant weeds in his/her fields (see, e.g. Dill et al., 2008). However, as weeds act as a common factor (Regev et al., 1976), appearance of herbicide-resistant weeds, or their control, depend on the weakest point of the system, i.e. the least effective farmer. The scale would depend on the potential range of spread by the weed (Perrings et al., 2002). As a result, from an individual farmer's point of view, investing in preventing the emergence of herbicide-resistant populations in a field, might not capture the future benefits of having avoided the costs of managing the herbicide-resistant weed (Llewellyn and Allen, 2006), especially in a situation of annual lease regimes. If the necessary cooperation between farmers is not enhanced, only adaptation or reactive measures can be taken. In a highly competitive context, preventive management needs an institutional setting that establishes regulations and responsibilities.

From a societal point of view, reactive measures favour those with the resources to adapt to new conditions while transferring risks to society and the environment (Perrings, 2005). Mueller et al. (2005) argue that glyphosate in conjunction with GR crops allows farmers to manage more hectares and increase overall productivity and profitability. However, this raises equity concerns, in particular those related to access to resources and finances. For instance, from the analysis of rural dynamics after the introduction of GR soybeans and the emergence of GR johnsongrass in Argentina, it can be argued that small and medium-sized farmers are left in a more precarious position. Having small plots makes them more vulnerable to the neighbourhood effect. Moreover, the economic and land tenure (e.g. annual lease contracts) structure discourages the farmers from investing in uncertain alternative practices, which require long-term planning or restructuring time. The environmental history of johnsongrass in Argentina shows that when it was not possible to control this weed, farmers directly abandoned the land or sold it.

As a result of the intensification of the agricultural model, the appearance of GR johnsongrass becomes a driver for further concentration while opening new markets for technology suppliers. Proposed strategies to deal with the situation rely on reactive measures, potentially causing a series of externalities. Impacts of the potential increment of herbicide use on human health and the environment should be further analyzed. The ‘chemical paradigm’ is again the keystone of the strategy. Since new herbicide developments seem to be in a deadlock, two routes can be followed if one wants to stay within this paradigm: either add one of the available herbicides to the glyphosate technological package directly, or incorporate the technology through the seed. In that sense, although aiming to overcome the effects of the previous GR crop generation, this ‘‘new generation” of GM crops strengthens the same paradigm. As a new magic bullet, this process may represent a new form of herbicide intensification: the ‘‘transgenic treadmill”.

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