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Technological lock-in in action: Appraisal and policy commitment in Argentina's seed sector

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ABSTRACT

This paper uses novel empirical evidence to analyse critically the widely held view that genetic engineering technology played a pivotal role in explaining the rapid expansion and increase in productivity of soy production in Argentina over the period from 1995 to 2015. We estimate the relative contribution of different approaches to seed innovation on soy performance over that period. We show how previous analyses have ignored the performance gains from plant breeding or misattributed them to genetic engineering. In our disaggregated assessment, seed innovations based on breeding techniques provide just as plausible an explanation for the expansion and performance gains of soy production. We illustrate how policy support to the seed industry is consistent with and is justified by mainstream narratives about the central role played by plant genetic engineering technology, and how the asymmetries created by these policy responses are contributing to the crowding out of plant breeding. This evidence, in our view, illustrates an important cognitive mechanism of lock-in to what may be a sub-optimal technology.

1. Introduction

Over the last thirty years the structure of the commercial seed industry has been utterly transformed. A sector that used to consist of tens of hundreds of small and medium sized seed firms is now dominated by just four agrochemical companies (Bayer, Corteva, BASF and ChemChina) which between them account for more than 60 % of the global proprietary seed market (Clapp, 2021; Howard, 2015). This dramatic shift has been associated with two parallel phenomena: the emergence and application of plant genetic engineering technologies, which have high research and development (R&D) and regulatory costs, and the extension of patent rights to cover new seed varieties developed using those techniques (Fulton and Giannakas, 2001; Schenkelaars et al., 2011).

The emerging oligopolistic structure of the seed agro-chemical industry together with the massive diffusion of seed varieties containing patented germplasm have generated a wide range of concerns. These include possible declines in R&D intensity (Schimmelpfennig et al., 2004), a shift of research and seed variety development towards the most profitable crops and markets and a reduction in seed variety diversity (Bonny, 2017; Howard, 2009; Kloppenburg, 2005), as well as, more generally, the undermining of farmer and agricultural sovereignty (Bjørnstad, 2016; IAASTD, 2009; Kloppenburg, 2010).From an innovation perspective, however, an additional and important concern relates to the technology specialisation adopted by the leading firms, in plant genetic engineering, and the possibility that innovation processes will be characterised by path dependency dynamics in which plant breeding approaches, that offer fewer possibilities to capture rents, are crowded out as firms specialising in genetic engineering come to dominate seed markets. This paper explores elements of this potential phenomenon based on empirical evidence from the seed sector in Argentina. Path dependency and lock in/out dynamics have been investigated at the level of agricultural R&D systems (Vanloqueren and Baret, 2009) and for technologies such as pesticides (Cowan and Gunby, 1996) but not between competing seed techniques, where we only have fragments of mostly anecdotal evidence that breeding programmes have been adversely affected by commitments to plant genetic engineering technology (e.g. Goodman, 2002).

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Specifically, we use empirical work on seed innovation in the soybean[1] sector between 1995 and 2015 to analyse critically widely held claims about the positive impacts of plant genetic engineering technology on agricultural performance, and to explore the role of those claims in contributing to policy commitments to that technology and, in turn, path dependency dynamics in the Argentinean seed sector.

Argentina was one of the first countries to commercialise genetically engineered (hereafter 'GE') seeds and it is now the world's third largest producer of GE crops, with almost all soy, maize and cotton production based on GE varieties (ISAAA, 2019). It is routinely claimed that GE seed technology played a pivotal role in transforming commodity crop production over the last two decades, soybean in particular, delivering large benefits to farmers, agricultural productivity, overall agricultural production, and the Argentinean economy (Ablin and Paz, 2004; Campos Motta, 2013; Leguizamón, 2014; Ministerio de Agroindustria de la Nación, 2019; Ministerio de Economía y Producción, 2004; Penna and Lema, 2003; Rodriguez et al., 2021; Trigo, 2016; Trigo and Cap, 2003). This is a very widely shared view, but it is one that we will challenge in this paper.

To do so, we distinguish between two approaches that have been used to innovate with soybean seeds in Argentina during the period analysed: *genetic engineering* and *plant breeding.*[2] We analyse evidence about the different innovations obtained using those two approaches, and assess how these have affected the expansion of soy production over the period analysed.

Our empirical analysis suggests that innovations based on plant breeding have been as important or more important than GE technology in explaining the Argentinean soy boom. This evidence contrasts markedly with existing claims about, and appraisals of, the impact of technological change on Argentinean soy production which have almost entirely ignored the possible role of plant breeding (Rodriguez et al., 2021; Trigo, 2016). We then show how policy commitments to GE technology that are consistent with, and justified by, claims about the pivotal role of plant genetic engineering in enhancing production and productivity growth might be crowding out firms specialising in plant breeding, and plant breeding efforts more generally.

Conceptually, our analysis is situated in debates about the importance of technology options and choices, and how appraisal can serve to variously open up or close down recognition of such choices (Bell, 2009; Glover, 2010; Stirling, 2008). Our argument is that narrow forms of appraisal reinforce and justify the assumption that GE technology is the only significant novelty as far as seed innovation is concerned, encouraging and validating policy commitments that privilege that technology, and so in turn the risk that that assumption becomes a self fulfilling prophecy. And yet narrow forms of appraisal assume their conclusions because by design they have ignored the potential role of other seed innovation techniques, which we argue have thus far performed as well as or better than GE technology. The evidence illustrates, in our view, an important cognitive mechanism of lock-in to what may be a sub-optimal technology.

Sections 2 and 3 briefly describe the conceptual framework of this paper and our empirical approach. Section 4 outlines existing accounts of the transformation of the soy sector in Argentina. Section 5 challenges those accounts by providing and analysing new evidence about some of the seed innovations that have been ignored within existing appraisals. Section 6 discusses how GE-centered accounts of the soy boom are reflected in resource allocation decisions and policy support for the seed industry and provides indications of the emerging longer term implications of those decisions for seed innovation. Section 7 provides the main conclusions.

2. Technological path dependence and appraisal

We are interested, in this paper, in technological options, how choices and commitments get made about those options, and the politics of those processes, especially in relation to appraisal. Many bodies of literature and practice concerned with technology and technology policy do not problematise technological choices, or they offer only a post-choice analysis of technology (Acemoglu et al., 2006; Malerba and Nelson, 2011; Rosiello and Maleki, 2021). The field of development economics, for example, is often concerned with how to reach the technological frontier in any particular industry, a frontier already chosen (but not usually questioned in that literature) by market leaders (Bell, 2009). Likewise, technology appraisal, which is often concerned with estimating the costs and benefits associated with adoption of a technology frequently does so by comparison to non-adoption scenarios, rather than to the costs and benefits of alternative technological or policy options that satisfy the same social objective (Stirling, 2010).

Our empirical analysis is informed by, and links, two sets of analytical ideas that do attend to issues concerning technological options, choice and commitment. One concerns the phenomenon of technological lock-in and path dependence, as identified in the evolutionary literature and other disciplinary traditions in technology studies (Cowan, 1990; David, 1985; Russell and Williams, 2002). Technological lock-in refers to a tendency whereby early technological choices, or an initial lead by one of two or more competing techniques, endure and become increasingly entrenched over time because of positive economic, cognitive, institutional and political feedback mechanisms. Such mechanisms result in path dependent change and can lock out alternatives, and this can be the case even when such alternatives perform in superior ways (Arthur, 1994; Unruh, 2000).

The second set of ideas is from a tradition of critical analyses of technology appraisal, rooted in science and technology studies. This emphasises how technology appraisal, despite pretensions to social neutrality, is necessarily framed by a series of normative assumptions and conventions (Felt et al., 2007). These concerns, for example, the scope of appraisal, the relevant questions to ask, or how notions of 'benefit' 'cost' or 'harm' are defined (Stirling, 2007). Such assumptions strongly influence appraisal outcomes, but they are often deployed tacitly, rather than set out explicitly as normative positions. As work in this tradition emphasises, the absence of a comparative approach to many forms of appraisal (including, routinely, impact assessments of GE seed technology) can obscure the appearance of technological choices (Stirling, 2007), but that characteristic is not a technical constraint on appraisal which could in principle be designed and conducted in other ways. Instead, the singular nature of appraisal may variously reflect choices, assumptions or habitual practice, for example in the form of legal or institutional mandates or prevailing, but under-examined ideas and expectations about what technological options, if any, are practically available, or even relevant (Stirling, 2010; van Zwanenberg, 2020).

Our empirical work links these sets of ideas by investigating whether and if so how choices or conventions about the design of appraisal might not only condition appraisal conclusions but also indirectly influence technological path dependency dynamics, in a context where competition between different technological options is characterised by uncertainty about their qualities and performance. To do so, we conduct a *reappraisal* of existing analyses of GE technology, but based on an alternative framing of the problem which compares technological options for improving seeds.

3. Data and methods

The core of our empirical analysis is a reappraisal of the contribution of seed innovation to the performance of soy production in Argentina over the period from 1995 to 2015. We explore the relative contribution of GE-based and breeding-based seed innovations to soy performance. This is not a straightforward exercise given the absence of appropriate

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[1] Soybean (also known as soy or soya) is the common name of Glycine max, a species of legume native to East Asia.

[2] The analysis does not relate to gene edited crops, as that technology was not diffused for soybean seed innovation in the period under analysis.

data. Our analysis, therefore, combines analysis of existing datasets with the collection of new evidence from interviews with scientists, civil servants and company managers.

We use datasets on plant certification and registration to characterise at a national level, the evolution over time of both the development of novel soy seed varieties and the market share of those novel varieties, distinguishing GE from non-GE varieties. The plant certification database registers the number of certification labels issued by the Argentinean National Seed Institute (INASE) for each seed variety each year. Owners of seed varieties that wish to commercialise a variety have to pay INASE to obtain a certification label for each bag of seeds they estimate they will sell each year. This information allows us to have a proxy of the market share of each seed variety per year. The plant registration database, known as the National Registry of Cultivars (RNC), contains information on the name and owner of each plant variety, its year of registration, country of origin, and, for some crops, other technological characteristics. In the case of soy, information is provided on whether the seed variety contains a GE trait and on the variety's maturity group (MG) . The latter correspond to latitudinal zones where soy varieties are best adapted.[3]

To complement this data we used information collected by the 'Red Nacional de Evaluación de cultivares de SOJA' (RECSO) published by the National Institute of Agricultural Technology. Data drawn from RECSO allowed us to characterise the evolution of the market share of soy varieties that have different growth habits (a characteristic that, as we shall explain later, has been altered in some soy varieties over the period under analysis through breeding).

The two plant certification datasets were used to analyse the evolution of seed innovations in Argentina during the period analysed, in terms of rate, type and innovating actors. In combination with information from RECSO the datasets was also used to run a correlation analysis in one region, the Province of Cordoba, to explore how the diffusion of plant varieties that incorporate different growth habits, and GE traits relates to the expansion of both land cultivated with soy and of soy production over the period from 1997 to 2010.

Additional qualitative and quantitative evidence collected through interviews enabled us to improve our understanding of: alternative plant breeding technologies and innovation; domestic productive and technological capabilities in soy seed production; the business and institutional setting of the soy seed industry in Argentina; existing policies and their impact on firm's investments in breeding; and the relevance of particular seed innovations to the performance and expansion of soy production in the country. Interviews were conducted within the context of three research projects[4] and included the Director of the National Seed Institute, senior scientists at the National Agricultural Technology Institute, and CEOs, managers and senior scientists at the seed firms Advanta, Don Mario, Nidera, ACA, Santa Rosa and Bioceres.

In the empirical analysis that follows we draw on the experiences of four of those seed companies: a) Nidera, a multinational headquartered in Argentina until 2014, specialised in plant breeding, that held around half the domestic soy seed market during the period from 1995 to 2015; b) Don Mario, an Argentinean firm created in 1982, also specialised in plant breeding, which had an insignificant share of the Argentinean soy seed market in the early 1980s, but became the largest soy seed provider in South America and a major player in the global soybean seed market; c) Bioceres Crop Solutions (Bioceres), an Argentinean agriculture biotechnology company that specialises in plant genetic engineering, created in 2001 by an association of farmers. The company collaborates closely with domestic public scientific institutions and in 2018 obtained regulatory approval for drought and herbicide tolerant soybeans in Argentina, Brazil, Canada, Paraguay and the USA; and d) Santa Rosa, a small Argentinean seed company created in 1992 dedicated to breeding and production of soy and wheat varieties.

4. The soy boom in Argentina: a GE-centered explanation

Over the period analysed in this paper, from 1995 to 2015, national production of soy expanded fivefold, reaching nearly sixty million tons in 2015; the area of land sown with soy increased more than threefold, to 20 million hectares, and average yields increased by 46 %, reaching a maximum of 3.1 thousand kg/ha in 2014 (see Fig. 1). Those metrics positioned Argentina as the third largest soy producing country, the third largest exporter of soy, and one of the most efficient soy producers in the world.

Early on in that period, in 1996, Monsanto obtained approval in Argentina for a genetically engineered gene sequence (known as an 'event') that tolerated the herbicide glyphosate. That event (MON-04032-6) was incorporated into Monsanto's own commercially traded soybean varieties and into the varieties of several domestic seed firms. For domestic legal reasons, Monsanto was unable to patent its event, but other companies paid royalties to use it, to secure access to any future (patented) GE crop innovations from Monsanto (Qaim and Traxler, 2005). Within a few years almost all commercially traded soybean varieties contained MON-04032-6, and until 2012 that was the only GE event approved for soy in Argentina. In that year, a second Monsanto event combining both insect tolerant and herbicide resistant (MON-87701-2 × MON-89788-1) was approved, although it did not begin to be planted in any significant quantity until after 2015 - at the end of the period of our empirical analysis[5] (INASE's plant certification database).

Existing accounts and analyses of the rapid expansion and competitive performance of soybean production over the period 1995–2015 have associated the boom in soy production with the diffusion of a cluster of technologies and techniques comprising the glyphosate tolerant GE seed varieties, the herbicide glyphosate and zero tillage practices, the latter of which involves planting seeds into unploughed land containing the residue of the previous crop. Within this technological package, GE soy has been given a prominent, catalytic role (Bisang, 2007; Cohan, 2013; Ministerio de Economía y Producción, 2004; Regúnaga et al., 2003; Rodriguez et al., 2021; Trigo, 2011; Trigo, 2016). The following quote by Katz and Barcena in an introduction to a volume on GE crops in Latin America for the Economic Commission for Latin America and the Caribbean (ECLAC) summarises this point:

> …in the 1990s, soy production [in Argentina] doubled in just five years, thanks to the rapid expansion of the area planted and the spectacular spread of transgenic soy, *a factor to which practically all of the increase in production is attributable.*.
>
> (Katz and Barcena, 2004, p.30; our translation; emphasis added)

In another ECLAC volume, Bisang outlines why GE soybean varieties were the key driving factor:

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[3] MGs are identified numerically from II to IX, based on the soybean varieties' response to abiotic conditions such as daylight length and temperature.

[4] 'Opening Up Natural Resource-Based Industries for Innovation: Exploring New Pathways for Development in Latin America' (2010–2012) funded by the International Development Research Centre; 'Knowledge intensive business services associated to Natural Resource-based Industries' (2014) funded by the Inter-American Development Bank; and 'Private and public strategies for success in modern agri-food markets' (2020) funded by the Inter-American Development Bank.

[5] In the last year of our analysis, 2015, the event combining both insect tolerance and herbicide resistance (MON-87701-2 × MON-89788-1) started to be incorporated in soy seed varieties in Argentina, though still at a low pace. In 2015, 162 out of 186 soy seed varieties commercialized still contained just the MON-04032-6 event, explaining 85 % of seeds planted that year (INASE's plant certification database).

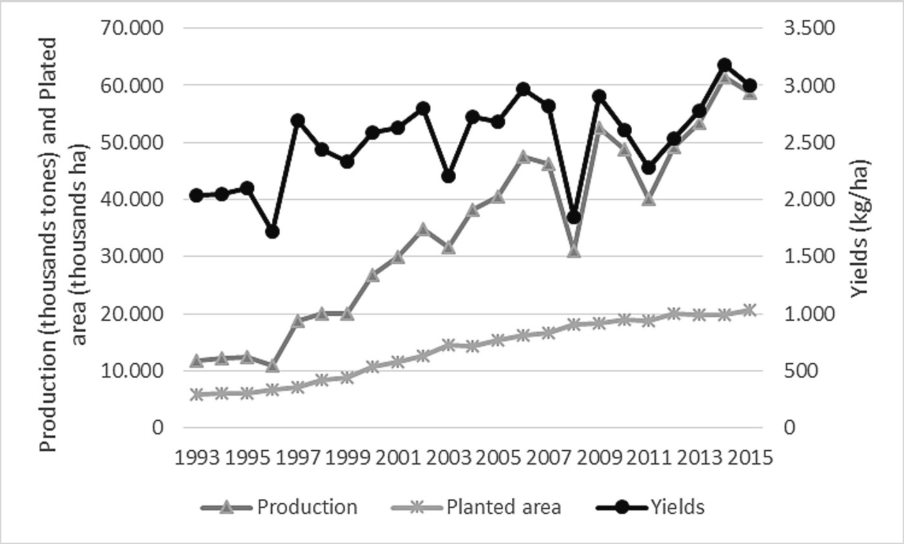

Fig. 1. Argentinean soy production, planted area and yield evolution – 1993–2015.
Source: Authors' visualizations based on data from Ministry of Agriculture of Argentina.

> Innovations (in the agricultural sector) began in 1996, when commercial transgenic soy resistant to glyphosate (RR soy) and Bt corn were released for sale … These allowed the massive spread of direct seeding [zero tillage], drove an increase in the demand of associated herbicides, and the application of biocide and a greater use of fertilisers. Thus, the new package, which was dormant, … became active with the entry of transgenic seeds, …
>
> (Bisang, 2007, p. 204; our translation)

Trigo (2016) has argued that the introduction of GE soybean varieties not only prompted the massive diffusion of zero tillage and glyphosate use, inducing a reduction in costs, but that this combination in turn facilitated the double cropping of soy with wheat because use of the technological package reduced the time between harvest of one crop and planting with another, enabling a virtual expansion of the area under soy cultivation. Based on that argument Trigo estimated that adoption of GE soy seeds produced US$ 112.8 billion of gross gains, as of 2016, on the assumption that GE seed technology *alone* explained an increase in the rate of the area sown to soy after the commercial introduction of GE varieties in 1996, and that it had also reduced farmers' direct production costs by US$ 5.4 billion, over the same period.

Those quantitative estimations have been reproduced in global assessments of the impact of plant genetic engineering (Brookes and Barfoot, 2009, 2018), and in turn by many other analysts, including prestigious international scientific bodies (EASAC, 2013). They have also been very influential - along with GE-centered explanations of Argentina's soy boom more generally - at the national level. Argentinean media representing a wide spectrum of political views routinely represents GE seed innovations as having driven a revolution in grain and oilseed production (e.g. Fuentes, 2016; Müller, 2000; Perfil, 2020; Ricciardino, 2008; Scaletta, 2006), as does the Argentinean government. In 2004, for example, the Ministry of Economy and Production attributed agricultural gains in production *entirely* to GE seed innovations —and emphasised the importance of sustaining this process by providing support for R&D in plant genetic engineering:

> "The rapid growth of grain production in the country, *due to the introduction of biotech varieties of RR [glyphosate tolerant] soybean and Bt corn,* has had an undeniable role in helping the country to mitigate the effects of the economic crisis that occurred in late 2001 and early 2002. ...In this way, the positive impact of biotechnology on society has been shown …*But it is necessary to ensure the sustainability of productive growth by allocating resources to encourage innovation in new varieties.*"
>
> (Ministerio de Economía y Producción, 2004; our translation, emphasis added)

Fifteen years later, the Ministry of Agroindustry continued to represent GE crop technology as *the* state of the art in seed innovation:

> "GM crops make it possible to increase the productivity, competitiveness and sustainability of agricultural practices, reducing the impact of agriculture on the environment, increasing food security and offering higher quality products to consumers. They also promote innovation and development."
>
> (Ministerio de Agroindustria de la Nación, 2019, p. 10; our translation)

The empirical analysis that supports the above arguments and ideas is frequently not made explicit, but it seems to be based only on:

- Estimations that suggest glyphosate tolerant GE soybean varieties have reduced production costs by about US$ 20 per hectare, mainly as a consequence of the fact that glyphosate is cheaper than the herbicides that would otherwise be used (Penna and Lema, 2003).
- Data on the diffusion of glyphosate tolerant GE soybean varieties which shows that those seeds were introduced commercially at the same time as other elements of the technological package diffused rapidly (especially zero tillage practices), and the rate of increase in soy production, the area sown to soy, and double cropping of soy with wheat all increased significantly (Trigo, 2016).

GE-centered accounts can be challenged on several grounds, such as the lack of justification of the claimed casual relationship between the diffusion of GE seed and increased production. The claim is that this occurs via (a) the role of GE varieties in accelerating the diffusion of other elements of the technological package, mainly zero tillage practices and (b) the effects of zero tillage and other aspects of the package on both the expansion of double cropping of soybean and wheat, and the expansion of new land devoted to soy production. Nevertheless, data on the diffusion of zero tillage suggests that although glyphosate tolerant seeds might have facilitated that diffusion, this was not a necessary condition. In Argentina, zero tillage began to diffuse in 1990 and then grew at a constant rate, which did not change significantly after the introduction of GE seeds in the 1997 growing season (Derpsch et al., 2010). Furthermore, long term analyses of the expansion of the soybean market in Argentina have attributed that expansion to other changes that happened prior to and after 1997. For example, increases in soybean prices (Lanteri, 2008) and an increase in the imports of other inputs, such as fertilisers, pesticides and agricultural machinery (Schnepf et al., 2001).

In this paper, however, we will focus on only one problematic aspect of GE centered accounts, which is that those accounts either ignore or only marginally recognise the role played by non-GE seed innovations. No information is provided in those accounts about the kinds of non-GE innovations that might have occurred during the soybean boom. In fact there is no readily available information about which breeding based innovations occurred, if any, in the period from 1996 to 2005 or about their impact. At best, possible innovations based on breeding are seen as playing only a supportive role; as providing well adapted background germplasm into which the GE trait, the radical innovation, has been inserted (e.g. Trigo, 2011, pp. 10–11).

5. Questioning the GE centered explanation

We now conduct a reappraisal of the Argentinean soy boom with data and information that seeks to differentiate between the impacts of GE and conventional breeding innovations. It is useful to begin, however, by discussing some key differences between breeding and genetic engineering.

Plant breeding essentially involves choosing individual plants that contain desirable characteristics ('traits'), crossing them, and then selecting the progeny for the desired combinations of parental characteristics. Basic selection of desirable crop variants has been carried out by farmers for millennia, and knowledge-intensive plant breeding for more than a century, resulting in an accumulation of valuable traits over time in agricultural plants. Plant breeding can now draw on several genomics-based techniques, such as marker assisted breeding and genomic selection. One set of those new genomic-based techniques, *genetic engineering*, involves a qualitatively different approach to improving seeds. Instead of relying on processes of sexual reproduction to alter the genetic makeup of a plant, it uses molecular techniques to identify, isolate and alter genes (that code for desirable traits), and to insert these directly into the genome of a plant.[6] The techniques enable genes from any source, including unrelated species, to be transferred to plants.

In practice, genetic engineering is always used in conjunction with plant breeding because the innovative output of genetic engineering is not a new plant variety per se but rather what is known as a GE 'event' -an engineered gene sequence that has been incorporated into a host genome. In order to create commercially viable GE varieties, the gene sequence must then be backcrossed, using plant breeding methods, into high performing 'elite' plant varieties (Suza and Lee, 2021). Those elite varieties will contain numerous other agriculturally valuable traits that are the outcome of both historical and, in many cases contemporaneous, plant breeding efforts. Furthermore, GE varieties will often be further improved upon using plant breeding techniques. Since any offspring of that breeding process will also inherit the engineered gene sequence they will remain GE varieties. This means that what is termed a 'GE seed variety' will often be the result (above and beyond the historical accumulation of traits) of two types of novelty: an engineered gene sequence, as well as new traits developed through plant breeding. Indeed, for some GE seed varieties, the engineered gene sequence may have first been introduced into a parent line 15 or 20 years ago, such that any recent novelty will be due to conventional plant breeding alone. The above points are important to appreciate when interpreting the impact on agricultural performance of 'GE seed varieties'.

Innovation strategies based on genetic engineering are often represented as providing a more promising basis for improving seeds than those that are reliant on plant breeding alone (Baulcombe et al., 2014; FAO, 2004; United Nations Development Program, 2001). Two sets of claims are typically articulated to support that representation. One is that GE can improve the *process* of seed innovation, on the grounds that it is more precise and efficient than plant breeding, whilst a second is that GE can improve the *outcome* of seed innovation, because it is able to draw on genetic variation that is not present in sexually compatible crop relatives (Moose and Mumm, 2008; Royal Society of London et al., 2000; Smith, 2000).

We, like many other commentators, would challenge those two assertions. Claims about increased precision and efficiency rely on the fact that genetic engineering draws on genomic knowledge. Yet, plant breeding is able to exploit advanced knowledge in molecular biology too, increasing the precision and predictability of plant breeding, and reducing the time involved in creating a new variety, as many individual scientists and scientific associations are careful to point out (Beddington, 2010; Biochemical Society, 2011; McCouch et al., 2013; Morrell et al., 2012). Claims about improved outcomes, on the other hand, are largely dependent on expectations about what the technology might be able to achieve in the future. For now, at least, the key traits achieved by genetic engineering, such as for herbicide tolerance and pest resistance, have been introduced in major food crops by advanced breeding techniques too (Arundel, 2001; Brumlop and Finckh, 2011; Zamir, 2008), whilst important traits such as intrinsic yield can so far only be improved using breeding techniques. Of course, there may in the future be desirable traits that can only, or more easily, be obtained using genetic engineering but the key point is that we cannot and should not assume a priori that germplasm alterations produced using GE techniques must or will be uniquely valuable or more efficiently obtained, compared to those produced by advanced breeding techniques.

Strongly linked to both the above assertions, and to the fact that plant genetic engineering is always used alongside plant breeding, is a tendency on the part of many analysts to treat the two sets of techniques as complementary rather than competing ways of improving plants (Ablin and Paz, 2004; Bisang, 2007; Trigo, 2011). However, we think that for certain purposes it is vital to distinguish between genetic engineering and breeding, and to think about them separately and as potentially competing techniques, in part because both can deliver valuable innovations, but also because they involve different processes, capabilities and market contexts and, particularly importantly, because they are subject to different institutional rules.

One of those rules concerns licensing. Since plant genetic engineering involves naturally unprecedented means of combining genetic material, novel GE events are subject to very expensive biosafety regulations. A 2010 survey of seed industry executives suggested that biosafety regulation costs are between 10 and more than 100 million US $ per novel event, which represents up to 80 % of overall R&D and commercialization costs (Schenkelaars et al., 2011, p. 35). By contrast, seed varieties obtained through plant breeding are subject to simpler, far cheaper licensing procedures.

Even more important are the rules concerning seed intellectual property. The novel events created using GE techniques can be patented in most countries; a condition of the 1995 Trade-Related Aspects of Intellectual Property Agreement. This enables the patent holder to block use of its GE event by competing seed breeders, or to license its use in return for royalties from sales of all derived varieties that contain the GE event. By contrast, the intellectual property rules governing traits and new varieties created by breeding permit conventional varieties, and the new traits they contain, to be freely used by competing firms in their own breeding programmes.

The differences in these rules for seed innovations based on genetic engineering versus those based on breeding have critical consequences for seed firms' incentives, investment decisions and business models, and in turn, the structure and evolution of the seed industry and its products.

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[6] A second generation of genetic engineering techniques, known as genome editing, also involves making direct changes to the genetic material of an organism without sexual reproduction.

These are issues which we return to later. For now, however, it is sufficient to emphasise that these differences mean it is, in our opinion, vital to try and distinguish between the contribution of GE and plant breeding when estimating the impact of seed innovation on agricultural performance.

5.1. *Re-examining the empirical evidence from Argentina*

We begin our reappraisal of the contribution of seed innovation to Argentina's soy boom by using data on plant registration and plant certification to begin to identify the different kinds of innovations introduced in soy seeds over the period from 1995 to 2015.

5.1.1. *Evolution of soy seed innovation in the Argentinian market*

In parallel with the expansion of both yields per hectare and the area planted with soy, there was a significant increase in the rate of innovation in soybean varieties. Fig. 2 shows the number of all *new* soy seed varieties registered in the RNC in the country over the period from 1982 to 2015. This data reflects the dynamic nature of innovation activity: new registered soybean varieties rose from about 15 per annum in the 1980s to around 40 per annum over the ten years from 2005 to 2015.

A key question is which kinds of innovations justified these new registrations? As mentioned earlier, and shown in Table 1, there was a significant increase in the share of seeds in the market that contained a GE event after 1996, rising from 22 % in 1998 to 98 % in 2002. That data can be, and often have been, interpreted as showing that the only novelty with respect to varieties classified as GE arises from the introduction of Monsanto's glyphosate tolerant event, MON-Ø4Ø32-6 . However, the novelty that permitted those seed varieties to be registered and certified as a *distinct* variety (a condition of the seed licensing law)[7] might also be due to additional traits introduced into germplasm that *already* contained MON-Ø4Ø32-6. It is a challenge to quantitatively and qualitatively identify those latter innovations with the existing information because plant certification data only distinguishes between seed varieties that contain GE traits and those that do not. The existing data, however, can be used to provide a rough estimation of the number of non-GM innovations introduced in the period.

In 1996, at the time Monsanto's event was first licensed for use in Argentina there was a stock of 204 soybean seed varieties that were registered in the RNC (Table 1). Since the glyphosate resistant event has to be backcrossed into existing varieties in order to be released into the market, this is the maximum possible number of new varieties registered after that point in time whose novelty might be explained exclusively or in part by the incorporation of the GE trait (MON-Ø4Ø32-6).[8]

Nevertheless, between 1996 and 2013, 665 new soybean seed varieties were registered, 563 of which contained the glyphosate resistant trait. Given that only 204 varieties were in stock until 1996, and so could have been registered as distinct once the novelty provided by the glyphosate resistance trait had been incorporated, the remaining 369 GE soybean varieties registered as new and therefore distinct between 1996 and 2013 must have incorporated additional improvements, obtained through breeding, over and above the fact that they contained the GE trait MON-Ø4Ø32-6 conferring glyphosate tolerance. This implies that at least 64 % of seed innovations (or features of novelty) in the Argentinean market after 1996 were created by breeding techniques. Nevertheless, accounts that seek to explain the increase in soybean production and productivity over this period by reference to a new 'technological package' do not mention the majority of the seed innovations that have occurred.

Of course, an important question concerns the significance of those breeding-based innovations, or rather their significance relative to the incorporation of the glyphosate tolerant trait. We now explore that question by reference to an analysis of qualitative data.

5.1.2. *Soy seed innovations developed through plant breeding*

Interviews with key informants in the seed sector and new secondary data enabled us to identify some of the important soybean innovations achieved through breeding in the period from 1995 to 2015 and to understand their significance. One of the most important involved changes to the growth patterns of soy. As noted earlier, soybean varieties belong to different maturity groups (MGs), each of which were, by the mid-1990s, suited to particular latitudes. In Argentina, for example, MGs II–IV were grown in the Pampeana South; MGs III- VI in the Pampeana North and MGs IV- IX in the North.

A key achievement by the Argentinean seed company Don Mario was the development, using advanced breeding techniques, of 'short cycle' varieties adapted to regions that historically only produced soy using high MG varieties. The new short cycle varieties were widely and rapidly adopted in those regions (northern Argentina, as well as southern Brazil) because they generated both higher yields and total production. This was for two reasons: (i) better disease resistance —in part because the short cycle varieties were already resistant to important diseases— but also because their shorter life cycle meant that they are less exposed to the diseases and fungi that appear towards the end of the sowing period; and especially (ii) because short cycle varieties facilitated double cropping of soy and maize where it was already practiced and allowed double cropping in regions where it was not previously possible (Marin et al., 2015).

In addition to belonging to different maturity groups, soybean varieties can have either determinate or indeterminate growth patterns. When determinate varieties flower, vegetative growth stops and only reproductive growth (i.e. flowering and the production of fruit pods) continues. Indeterminate varieties, by contrast, continue with vegetative growth after the plant flowers and the pods set, until the weather dictates the end of vegetative growth. An advantage of indeterminate soybean varieties is that they can recuperate after periods of dry weather, and so they yield better under those conditions. In addition, indeterminate varieties mature approximately two weeks earlier than determinate varieties, and this provides more time to plant a second crop after soy. In Argentina, soybean varieties MGs IV and below have traditionally been indeterminate whereas soybean varieties in MGs V and above have been determinate.

A second key innovation by the (at that time) Argentinean seed firm Nidera, was the introduction of indeterminate traits, using breeding techniques, into varieties within MGs V to VII; maturity groups that worked well in the Pampeana North and North Regions. Fig. 3 shows the rate of diffusion of the new indeterminate varieties of MGs V-VII over the period from 1997 to 2012, based on the RECSO data set which provides annual information on different productive and technological characteristics of commercially traded soybean varieties. The share of those indeterminate varieties increased across the whole period, from 10 % of all MGV-VII varieties in 1997 to 70 % in 2011, with the period of most rapid diffusion occurring between 2002 and 2011.

As discussed earlier, influential analysts have often attributed the post-1997 growth of both the area cultivated with soy and the overall production of soy (and sometimes even productivity growth) to the diffusion of the glyphosate resistance trait in soybean varieties. However, after 2001, when the event that confers resistance to glyphosate was already fully diffused within soybean varieties, the most important phenomenon we observe was the diffusion of indeterminate high MG varieties, at least in those parts of the country where high MGs work well, which are also areas that have experienced the most significant expansion in both the area cultivated with soy and double cropping of soy and maize.

It is useful to take the example of Córdoba Province, a soy producing region in the country where varieties of MG V-VII work well. Fig. 4

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[7] Varieties have to be distinct (i.e. novel), uniform and stable to be registered.

[8] Companies and public institutions register all their varieties with commercial value and imports of new varieties were not significant phenomena during the period under analysis.

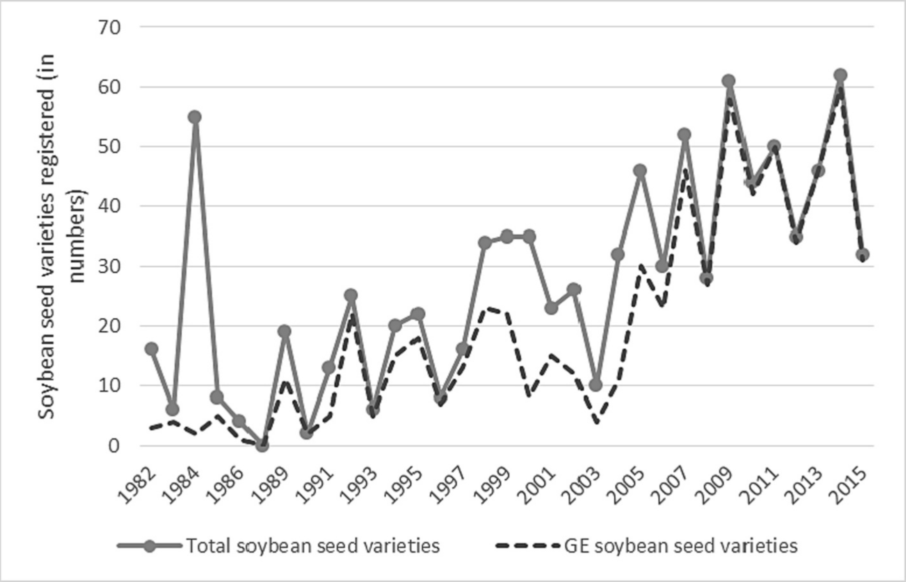

Fig. 2. New soybean varieties registered in the National Registry of Cultivars (RNC) in Argentina (1982–2015).
Source: Authors' visualization based on RNC database.

Table 1
Evolution of soybean varieties registered in Argentina (1996–2013).

Period	Total soybean varieties registered	GE soybean varieties registered
Accumulated 300 Up to 1995	204	0
1996–2000	143	73
2001–2005	144	138
2006–2010	235	211
2011–2013	143	141
Up to 2013	869	563

Source: Authors' own specification based on RNC database.

shows the increase in the share of both indeterminate varieties and glyphosate resistant varieties in Córdoba, whilst Fig. 5, shows the evolution of soy production and land cultivated with soy in the province over the period from1997 to 2010.

If we divide the time range in two, before 2002 and after 2002, then in the first period it is clear that the most important phenomena was the rapid diffusion of GE soy varieties, but in the second period, the most important was the diffusion of indeterminate varieties. Both total soy production and the area cultivated with soy, however, continued expanding throughout the whole time period.

Table 2 shows simple correlations, again working with data from Córdoba in this case, contemporaneous and lagged one year, between

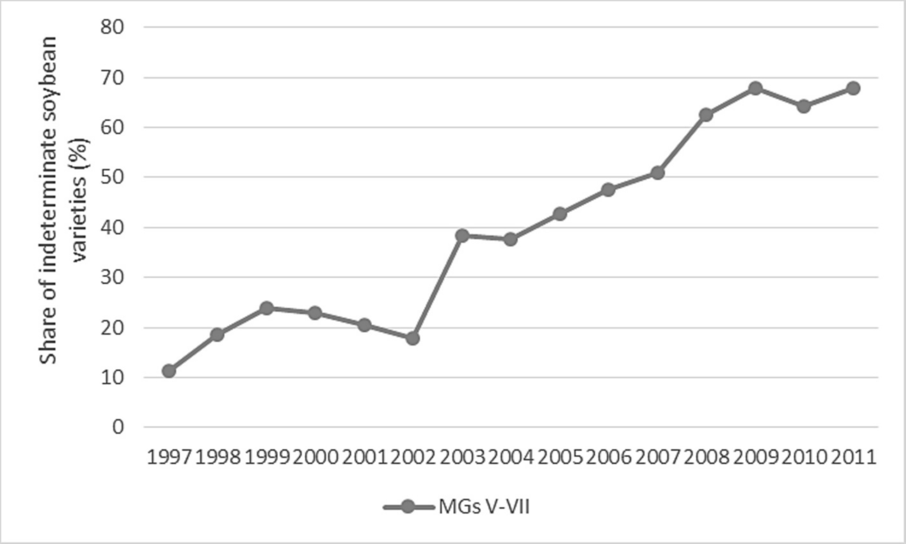

Fig. 3. Share of indeterminate soybean varieties by type of MGs in Argentina.
Source: Authors' visualization based on data from RECSO.

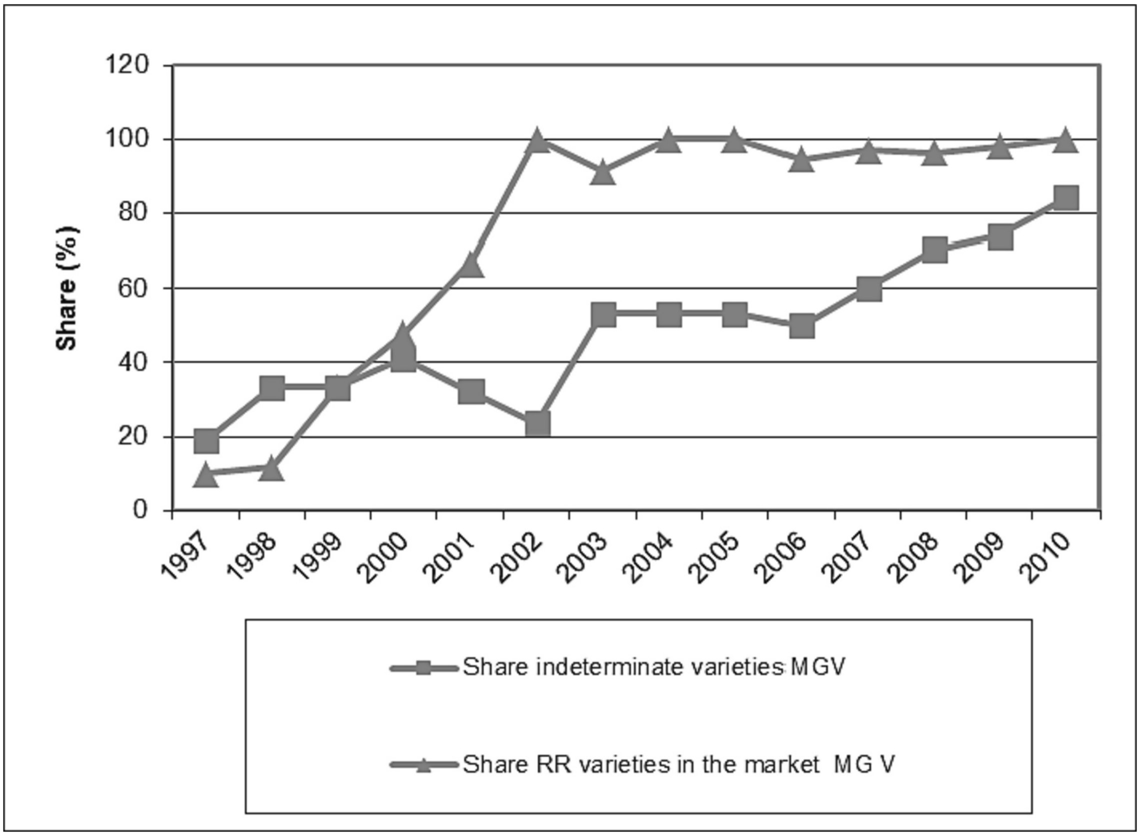

Fig. 4. Diffusion of indeterminate and glyphosate resistant soybean varieties in Córdoba: 1997–2010.
Source: Authors' visualization based on data from RECSO.

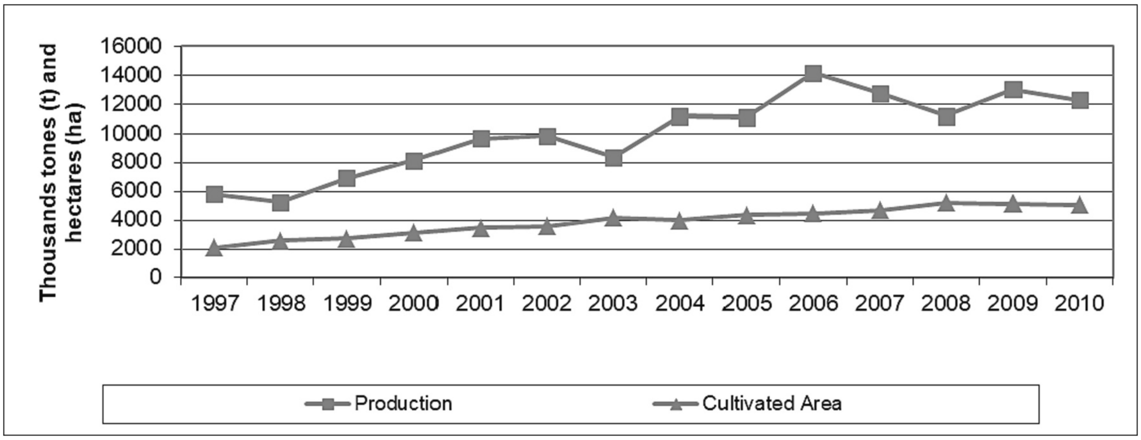

Fig. 5. Expansion of soy production and area cultivated with soy in Córdoba 1997–2010.
Source: Authors' visualization based on statistics from the National Ministry of Agriculture of Argentina.

(a) the rate of diffusion of indeterminate varieties (MG V and MG VI) and the increase in production and cultivated area (in columns 1 and 2) and, (b) the rate of diffusion of glyphosate tolerant soy varieties (MG V and MG VI) and the increase in production and cultivated area (in columns 3 and 4).[9] We divide the whole period analysed (1997–2010) in two: 1997–2002 the period of diffusion of glyphosate tolerant soy varieties and 2002–2010, when GE varieties were already fully diffused, and other innovations began to diffuse. We can see that before 2002 the expansion in both production and land cultivated with soy appears to be more closely related to the diffusion of glyphosate tolerant soy, whilst after 2002 the situation changes; the correlations are higher with the diffusion of indeterminate varieties than with the diffusion of glyphosate tolerant varieties. This is so for both contemporaneous correlations and correlations lagged by one period.

It is surprising that analysts of the Argentinean soy boom attribute all the increases in both cultivated area and soy production to the diffusion of GE technology, when there were other seed innovations diffusing at the same time. This is especially so when we take into consideration that one of those other innovations, the incorporation of indeterminate

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[9] Estimates with variables lagged by one year are more likely to capture the impacts of using an improved seed that will only have an impact the following season.

Table 2
Correlations before and after 2002, contemporaneous and lagged by one year.

		Share indeterminate MGV (i)	Share indeterminate MG VI (ii)	Share GE varieties GM V (iii)	Share GE varieties GM VI (iv)
Period 1997–2002					
Contemporaneous	Production	8 %	29 %	51 %	91 %
	Cultivated area	31 %	20 %	−3 %	94 %
Lagged 1 year	Production	69 %	4 %	−18 %	89 %
	Cultivated area	11 %	−61 %	46 %	94%
Period 2002/2010					
Contemporaneous	Production	39 %	46 %	30 %	27 %
	Cultivated area	91 %	9 %	37 %	28 %
Lagged 1 year	Production	67 %	40%	−2 %	28 %
	Cultivated area	67 %	40 %	−2 %	28 %

Source: Authors' own specification of indicators based on data from RECSO.

growth into certain maturity groups, appears to have just as much, or even more, potential to enable double cropping as the introduction of glyphosate resistance. There appears to be no particular reason why years of media, professional, and policy discourse about the transformation of Argentinean soy production should revolve around the term 'GM soy' instead of 'indeterminate soy.'

The two examples outlined above were not the only soybean innovations based on breeding techniques introduced over the period from 1995 to 2015. Important innovations in relation to disease resistance also occurred. For example, Don Mario developed soy varieties resistant to a disease known colloquially as Frog Eye disease (caused by the agent *Cercospora sojina*) which had begun to have an adverse impact on soy yields and seed quality throughout Argentina in the 2000s (Arias, 2011). Nidera bred and commercialized varieties resistant to Southern Steam Canker, which had caused severe damage in the years from 1996 to 1998 (Ploper, 2004).

The significance of the innovations noted above, as well as many other improvements obtained through breeding, can also be appreciated in relation to yield increases. Between 1998 and 2013, the average annual genetic yield gain of Don Mario's soy varieties was 1.63 %, totalling almost 23 % over that period (pers. comm., Don Mario, 2014), and for Nidera's soy varieties it was 1 % per annum, in higher MGs and 1.5 % in lower MGs (pers. comm. Nidera, 2014). Elsewhere we have estimated the monetary gains to farmers from these yield increases, on the basis of annual soybean crop prices (Marin et al., 2014). For the period from 1997 to 2016, we estimated a genetic yield-related monetary gain per hectare for soy farmers of about US$ 77 (Marin et al., 2014). Comparing these gains with the one-off cost reduction of US$ 20 dollars provided by the GE glyphosate tolerance trait (given that glyphosate was cheaper than alternative herbicides), suggests that about 80 % of the direct monetary gains to farmers, as a result of seed innovation over that 14 year period can be explained by novelty arising from plant breeding.

5.1.3. *The firms behind the innovations*

The success of some of the firms that introduced innovations using breeding techniques also reflects the value of those new traits. In 1995, prior to the introduction of the glyphosate tolerant GE event, domestic firms that specialise in breeding accounted for 70 % of the local soy seed market. Twenty years later, after the GE event that confers resistance to glyphosate was licensed, their share increased to 85 % (see Fig. 6). Within five years of the approval of the introduction of the glyphosate tolerant event in soy, in 2001, when virtually all soy varieties sold in Argentina contained Monsanto's glyphosate resistant event, soy varieties from Don Mario and Nidera continued to out compete Monsanto's own soy varieties in the final market. Don Mario and Nidera accounted, on average per year, for 71 % of the soy seed market during the entire period. The company Bioceres, which specialises in GE events, entered the soy seed market in 2010 with its own varieties, but did not gain a significant share (less than 1.5 %) and the domestic seed company Santa

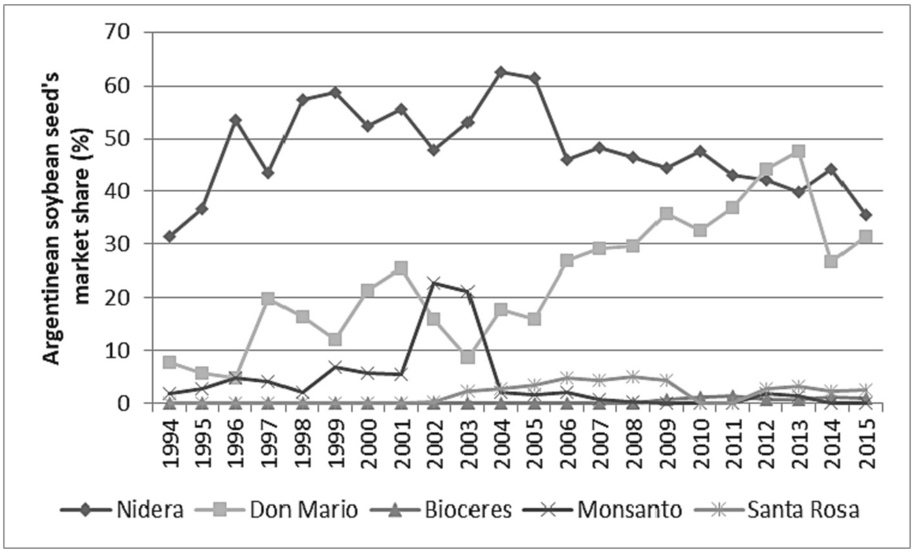

Fig. 6. Market share of selected soybean seed providers in Argentina (%) (1994–2015).
Note: Santa Rosa entered the soybean market in 2002 and Bioceres in 2010.
Source: Authors' visualization based on INASE's plant certification database.

Rosa, which entered the market in 2002, accounted on average for 3.2 % of the soy seed market over the period to 2015.

Some of these firms not only did well in the domestic Argentinian market but also elsewhere. For example, over a forty year period Don Mario, which originated as a small company from Chacabuco in the Province of Buenos Aires, supplying imported seeds to the domestic market, became the fourth largest supplier of soy seeds in the world, after the large global multinationals Bayer, Corteva and Syngenta. In 1993 Don Mario had only 20 employees and a negligible proportion of the domestic seed market. By 2020 the firm had 800 employees and subsidiaries in seven countries (Brazil, Uruguay, Paraguay, Bolivia, South Africa, the United States, and Italy); it had captured 55 % and 50 % of the Argentine and Brazilian soy seed market, more than 40 % of the Latin American market and 20 % of the global market. As explained above, this company was responsible for significant innovations during the period under our analysis (Marin et al., 2022). Don Mario's growth has been exceptional in a period in which many independent seed firms from both advanced and developing countries went out of business or were acquired by large MNCs.

6. Implications of GE-centered analyses for policy support to the SEED industry

The preceding analysis raises serious doubts about the validity of GE-centered explanations of the soy boom in Argentina. We have shown that there were a number of breeding innovations which were significant enough to have explained part of the technological contribution to the boom, or indeed most of it at some stages, despite those innovations not having been identified by other analysts, nor incorporated into existing explanations of the increase in soy production and productivity. We do not know the extent to which the introduction of indeterminate growth, or the capacity to mature early, for example, explains increases in production and productivity, relative to resistance to glyphosate, as this is a difficult estimation to run because the two innovations, together with others, were introduced *within* glyphosate resistant seeds. Our analysis is sufficient, nevertheless, to cast doubts on the narrative that resistance to glyphosate drove growth, because other very significant innovations diffused very rapidly at the same time, along with the success of the companies that were responsible for those other innovations.

Why is this important? After all, the outputs of GE and plant breeding techniques have been deployed within the same seed varieties - albeit with different kinds of firms responsible for the specific innovative outputs. We focus here on the implications of claims that GE technology has been pivotal in driving the soy boom for sustaining and/or justifying two kinds of policy commitments that have been important in the Argentinean context, as well as the implications of these commitments.

The first is the state's commitment to asymmetric seed intellectual property rules; namely the ability to patent GE events, but not the traits developed through breeding techniques, which can be used freely by competing firms. This asymmetry provides firms that can patent with relatively greater scope to capture rents and, at the same time, a legal instrument for shaping markets. We illustrate with some examples how this latter phenomenon has been playing out in Argentina.

Although Monsanto was not able to patent its glyphosate resistant event in Argentina, domestic seed firms agreed to negotiate royalties with Monsanto in order to have access to future (patented) events (Qaim and Traxler, 2005). Subsequent negotiations between Monsanto and domestic firms reflected the market power afforded by (future) patents. For example, during the period analysed in this paper about two thirds of the total value of soy varieties that have incorporated Monsanto's single glyphosate resistance gene were captured by Monsanto alone, even though, as suggested earlier, the trait in question was very unlikely to have contributed two thirds of performance gains compared to the other innovations incorporated in soy varieties by other firms. The remaining third was shared between plant breeders and the firms that multiply the varieties (Marin et al., 2015).

When, at the end of our case study period, Monsanto gained approval in Argentina for - and in this case patented - a second GE event for soy (MON-877Ø1-2 × MON-89788-1, known as RR2) which combined glyphosate tolerance with resistance to some insect pests, the company's ability to decide on what terms access to RR2 was granted to competing seed firms also illustrates the kind of market power and market shaping capacity enabled by patent protection. For example, Monsanto was able to insist, by way of contract, that Don Mario introduce its RR2 *only* into the top 15 % of the latter's most productive soybean varieties. Other researchers have described how Monsanto wanted to inflate the perception of the value of RR2, in a context where farmers were not buying the new technology because it was expensive, did not deliver significant management gains, and had relatively lower yields (O'Farell, 2020). As a member of a national agricultural producers association put it "RR2 cannot generate better yields, what Monsanto did well is to tell Don Mario to introduce the gene in the best varieties" (cited in O'Farell, 2020, p. 155).[10]

The experience of other seed firms is also revealing. For example, Santa Rosa, an independent seed breeding firm active in the soy seed market, was refused a license by Monsanto to use its RR2 event for two years, and the firm almost collapsed as a consequence (pers. comm. Santa Rosa, 2020). At least eleven independent domestic breeding firms in the soy seed sector have either gone out of business, or were purchased by the large global seed firms,[11] mirroring a trend globally in which independent seed firms are rapidly vanishing following waves of acquisitions on the part of the new global agro-chemical/seed firms that specialise in GE technology (Howard, 2015). The key point here is that governments are unlikely to alter the asymmetric intellectual property rules that gift a far more profitable business model and market power to the producers of GE technology if they and everyone else believe that it is the GE segment of the seed industry that is driving productivity improvements.

A second type of policy commitment sustained and justified by claims that GE technology has been pivotal in driving the soy boom concerns the pattern of subsidies for the seed sector. An illuminating example is the contrast in the support received by the joint public-private Argentinian company Bioceres, which specialises in developing GE events, and Don Mario, which specialises in breeding. Between 2003 and 2015, Bioceres and its laboratory INDEAR, received more than 45 grants from Argentina's Science and Technology Agency, totalling at least US$ 8.5 million, as well as other government loans with Inter-American Development Bank funding. Don Mario, by contrast, applied for funding several times, but received no support at all. Other key government resources were also exclusively allocated to Bioceres/INDEAR. For example, the first genomic sequencing equipment to enter the country was purchased by the government for INDEAR, at a time when most domestic plant breeding companies that sought to exploit advanced genomic knowledge could not afford such equipment. Neither Don Mario nor other breeding firms were able to benefit from the acquisition of that resource because INDEAR either sold its gene sequencing services at a higher cost than could be obtained from contracting the service abroad or did not provide the service at all (pers. comm. Don Mario, 2014).

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[10] Don Mario subsequently regretted having introduced the event into its most productive varieties and it took several years for them to breed it out (pers comm, Don Mario, 2018).

[11] For example, in 2008, Relmó, the first Argentinean company dedicated entirely to soy breeding with one of the most important soy seed banks, was acquired by the Pampa Agribusiness Fund, with headquarters in Canada, and the domestic seed firm SPS, that had 3 % of the local soybean seed market was acquired by Syngenta. One year later, Monsanto acquired Seminium, a local firm with a largely established brand in the soybean seed market that accounted for 4 % of the soybean seed market prior to its acquisition (Agrositio, 2008; Bertello, 2009).

The combined effects of, on the one hand, bestowing intellectual property rule-created advantages, such as more profitable business models, and market power over licensing agreements, on firms specialising in plant genetic engineering, and on the other hand, of directing public subsidies to such firms and away from those specialising in breeding, are significant. They have functioned so as to diminish the relative profitability and presence in the market of seed firms specialising in breeding alone. This is likely to lead to a gradual loss of plant breeding capabilities and it will favour investments based on creating and exploiting GE novelty. Although firms that specialise in developing GE events will engage in breeding activities themselves, in circumstances where there is less competition from other seed breeding firms, and where institutional rules allow them to capture rents from standardised GE innovations, they will have fewer incentives to continue to create variety diversity. In short, the policy decisions and commitments described above will contribute to technological lock-in dynamics that privilege GE-based trajectories of seed innovation and disadvantage breeding based solutions. What we wish to emphasise is the pivotal role of mainstream assessments of GE seed innovation performance in helping to create and sustain the prevailing belief that genetic engineering represents *the* frontier in seed innovation, and therefore the view that it is this technology that ought to receive privileged policy support and investment.

It is important to note that the consequences of such lock-in dynamics extend beyond the crowding out of breeding approaches by, quite possibly less promising, GE approaches. If firms specialising in GE seed innovation become the major (or only) market winners, key production problems and crops may be ignored entirely, with the result that the overall diversity of crop innovation will decline. This is because the very high regulatory costs of commercialising GE innovations mean that only certain kinds of GM crop innovations are potentially profitable. As one biotechnology industry executive emphasised in the early 2000s, those costs are such that a new GE crop trait needs to generate annual revenues, at peak sales, in the range of US$ 175–200 million in order for the large investments involved to pay off and that “[r]elatively few transgenic crop product concepts can achieve these high hurdle rates…” (Goure, 2004, p. 265).

In practice, only GE innovations that can be incorporated into major commercial crops, and that can command relatively high prices, for example because they substitute for other costly inputs such as herbicides, are likely to be viable. An Argentinean example illustrates this point well. In the 2000s, solutions to an important viral disease in maize, known colloquially as *el mal de Rio Cuarto*, were being sought in the R&D labs of both Don Mario, using a breeding approach, and Bioceres, through its joint INDEAR laboratory, using a GE approach. INDEAR subsequently decided to discontinue the project, despite making technical progress, because the required investment - across R&D, biosafety and patenting - would mean the project would not be profitable for maize varieties that could be sold only in one country (pers. comm. former Bioceres researcher, 2020). Don Mario, by contrast, continued its R&D project and managed to obtain and commercialise varieties resistant to the viral disease (pers. comm. Don Mario, 2020). What this example illustrates is that the absence of firms specialising in plant breeding, and/or circumstances where such firms are less profitable than they otherwise would be, will entail that seed innovation pathways will become far more narrowly focused, avoiding crops and traits that do not have large potential markets (cf Howard, 2009; Kloppenburg, 2005). Such a scenario will have seriously adverse consequences for the ability of the seed industry to solve many kinds of production constraints and to support a diversity of agricultural production systems beyond large scale commodity crop production.

7. Conclusions

Existing appraisals of the technological basis of the soybean boom in Argentina have ignored the potential contribution of plant breeding-based seed innovations to the performance of soy production. The prior assumption (whether overt or tacit) has been that plant breeding merely provides ‘background’ germplasm and that GE-based innovations are the only potentially significant novelty as far as seed innovation is concerned. Consequently, that assumption has effectively been reproduced in the findings of those analyses, as if it were an empirically based finding rather than an artefact of the ways in which appraisal has been conceived of and conducted. The effect has been to overlook the role and contribution of plant breeding in discussions about the technological basis of improvements in agricultural performance over the last three decades - and subsequently in policy decision-making about the seed sector. That problem has been further accentuated by the fact that the contribution of seed breeding novelty has not only been ignored but also partly misattributed to GE technology, thus inflating estimates of the performance of plant genetic engineering.

The absence of attention to plant breeding innovations might not matter if there were no trade-offs between investment, policy support, and innovative effort directed towards plant genetic engineering, and similar kinds of commitment to breeding-based options. Yet our argument has been that there are very likely to be trade-offs between the two approaches, in part because of the distinctive intellectual property rules governing the deployment of each set of techniques. Favourable intellectual property rights for GE crop technology act so as to privilege firms specialising in that technology and create relative disadvantages for firms specialising in plant breeding. This asymmetry has been further exacerbated in Argentina by decisions about the distribution of public subsidies and public investment between the two approaches to seed innovation, and the firms that specialise in those approaches. This path dependency dynamic is not trivial because the risk is not only that GE-dominated trajectories of seed innovation might be less useful than trajectories dominated by plant breeding, but also that they will result in less diversity, in terms of attention to different kinds of crops, agricultural problems and farming systems, given the very high costs of biosafety regulation.

The problem is not that GE crop technology does not work, in the sense of providing innovations that are of benefit to adopting farmers and other metrics of agricultural performance. Rather, it is that GE-centered analyses of agricultural performance, and their accompanying narratives, obscure the contribution of alternative, perhaps better performing approaches to seed innovation. By ignoring such alternatives, the impression is given to policy-makers and other actors that there are no other useful and valuable options or choices about the future of seed innovation beyond GE technology. We have argued that these ideas reinforce policy commitments to GE technology, and the relative inattention to alternative breeding based approaches, which then exacerbate path dependency dynamics in favour of GE technology.

Our broader, analytical intention in this paper has been twofold. The first has been to illustrate, in the field of agricultural technology, how assumptions about the design and scope of appraisal can variously open up or close down recognition of technological choices, and how singular forms of appraisal effectively reproduce prior unexamined assumptions about which techniques or technological options are most valuable. The second has been to understand the potential contribution of prevailing ideas about technological performance to technological path dependency dynamics; that is to mechanisms of cognitive lock-in. We have argued that the unexamined, but seemingly empirically supported, idea that GE technology is the only significant source of productive novelty in seed innovation is consistent with and justifies policy commitments to plant genetic engineering. Those commitments in turn shape the market environment in which firms operate - and so can and do contribute indirectly to path dependency and technological lock-in dynamics. The risk therefore is that the initial, unexamined (and empirically unsupported) assumption that GE technology is the only significant source of novelty in seed innovation starts to become a self fulfilling prophecy.

CRediT authorship contribution statement

Anabel Marin: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Supervision. **Lilia Stubrin:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **Patrick van Zwanenberg:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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