The Journal of Peasant Studies

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/fjps20

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Raquel Ajates

To cite this article: Raquel Ajates (2022): From land enclosures to lab enclosures: digital sequence information, cultivated biodiversity and the movement for open source seed systems, The Journal of Peasant Studies, DOI: 10.1080/03066150.2022.2121648

To link to this article: https://doi.org/10.1080/03066150.2022.2121648

THE JOURNAL OF PEASANT STUDIES
https://doi.org/10.1080/03066150.2022.2121648

Routledge
Taylor & Francis Group

From land enclosures to lab enclosures: digital sequence information, cultivated biodiversity and the movement for open source seed systems

Raquel Ajates[a,b]

[a]Universidad Nacional de Educacion a Distancia, Madrid, Spain; [b]University of Dundee

ABSTRACT
4th Industrial Revolution technologies that blur the lines across physical, digital and biological domains have entered seed systems. The digitalisation of seeds' DNA is generating the unstoppable growth of big data on digital sequence information (DSI). The paper analyses the legal vacuum for DSI, which aggravates the dematerialisation and fragmentation of seed, rendering it easier to control under legal, technological, social and logistical enclosures. Open-source seed is explored as a governance mechanism across physical and digital spheres. DSI emerges as a critical juncture for seed movements, revealing how the construction of seed and food sovereignty is a digital and technological affair.

KEYWORDS
Open-source seed; seed systems; 4th Industrial Revolution; digital commons; digital sequence information; seed sovereignty; enclosures; big open data; dematerialisation; digital feudalism; *in situ*; *ex situ*; *in silico*; res communis

Abbreviations

ABS: Access and benefit-sharing; AI: Artificial Intelligence; CBD: Convention on Biological Diversity; CGIAR: Consultative Group for International Agricultural Research; CRISPR: clustered regularly interspaced short palindromic repeats; DSI: digital sequence information; FAO: Food and Agriculture Organization of the United Nations; GATT: General Agreement on Tariffs and Trade; GOSSI: Global Open Source Seed System Initiatives; INSDC: International Nucleotide Sequence Database Collaboration; IPR: intellectual property rights; IR: industrial revolution; ITPGRFA: International Treaty for Plant Genetic Resources for Food and Agriculture; Multilateral System (MLS); NP: Nagoya Protocol; OSS: open-source seed; OSSS: open-source seed systems; PGRFA: plant genetic resources for food and agriculture; TK: traditional knowledge; UNESCO: United Nations Educational, Scientific and Cultural Organization; UPOV: Union for the Protection of New Varieties of Plants.

The Fourth Industrial Revolution: agriculture as the canary in the automation mine

> *Most aspects of farming are exceptionally labour-intensive, with much of that labour comprised of repetitive and standardized tasks – an ideal niche for robotics and automation*. (Brown 2018)

CONTACT Raquel Ajates raquel.ajates@poli.uned.es Universidad Nacional de Educacion a Distancia, Madrid, Spain

Building on the Third Industrial Revolution (IR) use of electronics and information technology to automate production, the current Fourth IR's digital revolution is characterised by a wide variety of technologies ranging from gene sequencing to nanotechnology, from renewables to quantum computing. The fusion of these technologies is blurring the lines between physical, digital and biological domains (Schwab 2016). The narrative is one of a suite of 'disruptive technologies' interdependent on each other, crosscutting and employing robotics, genetic engineering, artificial intelligence (AI) and big data (Schwab 2016; Barnhizer and Barnhizer 2019; Smith and Fressoli 2021).

Agricultural technologies, such as drones and tractors, with built-in sensors are increasingly designed to collect data on a growing number of metrics, and can carry out many jobs from seeding to spraying, monitoring and harvesting without human intervention (Carolan 2018; Brown 2018; WEF 2018; World Bank 2019; Carolan 2020). These networked technologies raise questions about commercially sensitive data ownership and security (Rotz et al. 2019). Embedded in the Fourth IR, the rapid growth of big data, AI and other frontier digital technologies is transforming not only the way and speed of industrial production, but also the way we are able to monitor nature, life and environmental changes. These changes are generating big data, and giving way to new digital enclosures and exclusions (Prainsack 2019). The crosscutting effects of the Fourth IR automation in food systems involves disruptive technologies that aim to control animal and plant organisms as well as the wider farming environment in order to tackle a variety of issues both created by and threatening the global food system, ranging from stagnated yields to diet-related disease and the current climate emergency (FAO 2017; King 2017; World Bank 2019; Iaksch, Fernandes, and Borsato 2021; Mehrabi et al. 2021; Hassoun et al. 2022; Woodward and Thomas 2022). The inexorable growth of networked technologies and big data come with serious issues around data misuse, power imbalances resulting in data asymmetries and concentration of big data ownership (Newton 2015; Prainsack 2019), raising concerns about the emergence of a new techno digital feudalism (Hassen 2010; Meinrath et al. 2011; Grimshaw 2017; Scott 2018). While more agricultural technology exists than ever before, the food system's wicked environmental, public health and social justice crises remain (Willett et al. 2019).

Concerns about the way food is intensively produced, highly processed and unequally distributed have intensified since the beginning of the Green Revolution, and especially since the 1980s, when food trade became progressively globalised and supply chains continued to grow longer (Friedman 2000; Lang, Barling, and Caraher 2009; Patel 2013). Concerns over seed conservation and farmers' right to seed have followed a similar path (Shiva 2020). Before the Green Revolution, seeds were overall free to save and share, with no legislative framework to regulate them (Fowler 2000). Global legal frameworks and intellectual property restrictions evolved to protect improved varieties developed by private companies. The introduction of transgenic crops in the early 2000s accelerated the development of the legal landscape by allowing patents on plants and by extending plant variety protection worldwide (Peschard and Randeria 2020a). The spread of these new controls over seed practices causedvast socio-economic impacts for farmers who now had to be able to afford seed purchases year on year. Proprietary seeds drastically reduced cultivated biodiversity too. Before, there were almost as many varieties as there were farmers. This diversity served as a buffer against diseases or environmental changes, but the legal obligation to use registered seeds creates dependence on multinationals and homogenises global crops. An estimated 75 to 90 percent of vegetable and fruit crop varieties have been lost over the last century (FAO 2019a). Furthermore, the rise of indoor growing, aquaponics, seedless fruits and cytoplasm male sterility, and the practice of adding external inputs such as fertilisers and pesticides, are substituting for seeds' natural ability to sprout, adapt and fight pests and disease.

Restrictions on seed diversity threaten the resilience of seed systems that were developed by civilisations over millennia. There is no bigger challenge to food security and human health than environmental breakdown and biodiversity loss. Seeds epitomise these risks but also offer opportunities for planetary and human health (Esquinas-Alcazar 2005). Seeds are the basis of food growing, and the essential constituent of the plant-based diets humans should switch to in order to live healthily within planetary limits (Willett et al. 2019). However, the loss of natural habitats, combined with the professionalisation of breeding and seed saving as activities separate from farming, has culminated in a severe loss of biodiversity, much needed to survive in the current climate emergency. Instead, the industrial model of food production has resulted in a high degree of homogenisation of varieties and market concentration with the aim of reducing capital risks and increasing yields. Selecting for, or engineering, variants has created some desirable traits in some plants and fungi, but at the cost of reducing their genetic diversity, decreasing their resilience and reducing the pool of variation available for the future. Conservation of genetic biodiversity is thus an essential counterpart of crop improvement and is essential to ensure that crop species retain resilience to emerging threats (Kersey et al. 2020).

This brief introduction has set the scene on how Fourth IR technologies are speeding up trends in an already highly mechanised and concentrated industrial food system. I now turn to introduce how the rise of digitalisation of plant genetic material, often referred to as digital sequence information (DSI), and the Parts Agenda of synthetic biology research have generated disruption and a legal vacuum in the international governance of plant genetic resources for food and agriculture (PGRFA). Acknowledging the ongoing growth of DSI within this milieu, I analyse the socio-economic, environmental and political tensions that the digitisation of seed material generates. I then present the concepts of appropriation and substitutionism and apply them as a theoretical framework to illustrate how DSI is part of a series of mechanisms of the different IRs that have been used to control nature and food production cycles, as well as over PGRFA. I present an overview of the dire state of global seed systems from a multilevel perspective, and delve deeper into how additional processes of dematerialisation and fragmentation have played out in seed production and conservation, moving between physical and digital spheres through DSI, and exacerbating their appropriation and substitution. I provide an analysis of the open-source seed (OSS) concept and movement that is emerging globally, and how it maps out against identified challenges and opportunities in seed system governance in the context of DSI. Finally, I offer some conclusions on the challenges and opportunities ahead for securing seed sovereignty and cultivated diversity.

For this research I build on and review the latest multidisciplinary literature on DSI, including economics, international law, synthetic biology, conservation studies and critical agrarian studies, as well as on official policy reports on the topic and the conventions and treaties that establish the current rules – and lack of rules in the case of DSI – for the governance of biodiversity and PGRFA. The article employs document analysis to frame the debate around DSI in critical agrarian studies discussions of the corporate and capital control of food production, taking into account the benefits and challenges of big open data and sequencing technologies.

The paper makes three contributions: First, it highlights the importance of considering DSI not as a new, distinct issue, but a continuation of the appropriation and substitution of natural processes and elements of food production through dematerialisation and fragmentation. DSI is the latest output of the new technologies of the Fourth IR. DSI allows accumulation of PGRFA in a way and at a speed that *in situ* (in the natural habitats where they evolved) or *ex situ* (in gene banks) conservation methods did not allow due to their cost and complexity. Second, the paper considers the case of the copyleft-based OSS model – currently only used in initiatives using physical seeds – for the governance of digitalised PGRFA. Third, in a fact-finding study for the Convention on Biological Diversity (CBD), Bagley and colleagues (2020) found a limited production of interdisciplinary and integrated research on DSI relating to farmers' rights, a gap this research contributes to filling by offering an integrated perspective on the topics of food, data and technology sovereignty.

Seed wars go digital: the rise of digital sequence information

From the beginning of the Green Revolution, seed was seen as an important vehicle for the dissemination of technology, both the technology embedded in the seed itself (e.g. shorter and sturdier stems in rice and wheat), and the technology that was sold as a set along with improved varieties, such as chemical fertilisers and pesticides (Louwaars 2002). Nowadays, in the Fourth IR – sometimes termed Industry 4.0 – big data has emerged as a new product in itself, and food and seed systems have not escaped the trend (Naeem et al. 2022). Building on genetic modification and CRISPR-Cas9[1] techniques, the reduction in cost of gene sequencing technologies is allowing technological advancements that enable the reproduction of seeds' DNA in virtual format, referred to as DSI, generating big PGRFA data sets (Cabrera Medaglia 2020; Kersey et al. 2020; Hassoun et al. 2022).

These new technologies have triggered a controversy around the governance rules that should regulate the access to DSI and the fair and equitable share of benefits arising from their utilisation, as established in the third objective of the CBD (Montenegro de Wit 2016; von Wettberg and Khoury 2020; Vogel et al. 2021). Finding a solution to this controversy is urgent, since a continued fall in the cost of genome sequencing is expected, which will bring with it an increased availability of high-quality reference genomes (Kersey et al. 2020). While DSI comes from material PGRFA, and can bematerialised again, it can now have value without needing to recover its materiality. Thanks to DSI, genetic information can be replicated and experimented on without movement of, or access to, physical seeds. Big data, rather than seed, becomes the product.

The heated international policy debate on whether the meaning of the term 'genetic resource' in the current legal framework includes DSI or only physical PGRFA started in

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[1] Clustered regularly interspaced short palindromic repeats (CRISPR) together with CRISPR-associated protein 9 enzymes (Cas9) form the basis of CRISPR-Cas9, a technology that allows the removal, addition or alteration of sections of DNA in an organism in an accurate, fast and low-cost manner. This technique is not suitable for plant systems yet as it is currently unlikely to produce sufficient phenotypic change (Zhu, Li, and Gao 2020).

2015 (ETC 2018) and has been intensifying since. DSI is not a term typically used by the scientific community, but it has become adopted as a placeholder in policy negotiations (Smyth et al. 2020). Terms more commonly employed by scientists to refer to DSI include genetic sequence data, nucleotide sequence data, nucleotide sequence information and genetic sequences (Wynberg et al. 2021). Critically, no precise definition for DSI exists under the CBD, the Nagoya Protocol (NP), or the International Treaty for Plant Genetic Resources for Food and Agriculture (ITPGRFA), the three main international legal mechanisms that regulate access and benefits arising from biodiversity and PGRFA. In the 2019, for the first time in its history, a Governing Body session of the ITPGRFA was finalised without a closing session due to delegates being unable to agree on the terms for an enhanced access and benefit-sharing (ABS) system that would include DSI (Cabrera Medaglia 2020; Wynberg et al. 2021). DSI/genetic sequence data and rates for benefit-sharing payments still remained the main outstanding issues at the Ninth Session of the Governing Body of the ITPGRFA celebrated in India from 19th to 24th September 2022 (IISD 2022). The collapse in negotiations has extended the legal vacuum period during which companies are able to continue to grow their big data sets of DSI. In the meantime, initiatives such as DivSeek, launched in 2012, have been sequencing plant genetic material held in national and international gene banks, originally collected from farmers' communities under the assumption that it would remain in the public domain. DivSeek is a collaboration of 69 institutional and corporate members (including multinationals such as Bayer Crop Science and DuPont Pioneer),contributing to the corporatisation of these big data with no mention of access and benefit sharing (Peschard 2016; Mooney 2018). While the DSI debates continue, the progress of DivSeek is developing at a speed, with a Memorandum of Understanding for collaboration between the initiative and FAO on behalf of the ITPGRFA having been signed in June 2022 (DivSeek 2022).

There is a growing body of literature documenting all angles of this debate, with scholars from different disciplines putting forward arguments for the inclusion or the exclusion of DSI in the ABS framework of the CBD, which will then likely affect how the ITPGRFA deals with DSI. High-income and DSI-research-active countries argue that is essential to maintain a conceptual and definitional distinction between physical genetic material and data associated with that material, claiming that the creation of the latter requires resources and skills added by researchers; in the words of a European Seed Association representative: 'DSI does not appear naturally like the morning dew, a person has to access equipment and expend effort and time to generate it. That effort also needs to be accounted in value determinations' (European Seeds Association – in Nawaz, Satterfield, and Hagerman 2021). This perspective sees DSI as human-made. Those with an opposite view see DSI as an inherent part of PGRFA, with its value deriving from a historical stewardship of resources, and call for a halt to the long colonial legacy of biopiracy – not just of physical material, but also of knowledge and information (Bond and Scott 2020; Nawaz, Satterfield, and Hagerman 2021). The mere existence of DSI is dependent on the prior existence of the physical entities, and thus the generation, use and commercialisation of DSI should be regulated to avoid further appropriation.

The 'Parts Agenda', a research stream within synthetic biology, is used as a key argument to exclude DSI from the ABS. In this line of research, genetic resources are fragmented into their smallest functional units to create standardised, interchangeable 'bioparts' that are both material and immaterial, generating building blocks for assembling more predictable and easier to control synthetic ‘biological devices’[2] (Rourke 2021). ‘Biobricks’ are the most popular bioparts. Biobrick DSI was initially open access through the Registry of Standard Biological Parts, but soon found problems, and access became regulated (Rourke 2021), pointing out that mere open access does not equal fair use of data. Another issue with biobricks is that the legal obligations of users of genetic resources to share benefits with countries of origin can apply to bioparts that were synthesised in the laboratory using downloaded genetic sequence data, and using multiple fragmented bioparts spliced together with elements from other genetic resources, each originating from different countries with different rules on DSI. Some scholars argue this method could lead to the accumulation of traceability problems in a single synthetic product, particularly in ‘systems’ of several biological devices, in which cases benefit-sharing obligations could start to ‘stack’ from the various bioparts (Rourke 2021). The likelihood of any benefits being channelled to originating nation states in a fair and equitable manner is minimal (Laird et al. 2020; Nawaz, Satterfield, and Hagerman 2021; Rourke 2021). The titanic bureaucracy that would ensue would likely restrict access to and use of DSI, resulting in slow innovation or applications (Gaffney et al. 2020; Laird et al. 2020; Scholz et al. 2020; Cowell et al. 2021; Wynberg et al. 2021).

A further argument put forward against the inclusion of DSI in the ABS is that many popular bioparts used in plant synthetic biology are from plants that have been used as model organisms for a long time, and grown in the laboratory for many generations prior to the entry into force of the CBD, Plant Treaty or the NP. Thus, since the basis of new biological devices was appropriated at some point before the current benefit-sharing framework existed, a call for retrospective regulations might be required. Bagley and colleagues (2020) have carried out a detailed review of the current legal regulation of DSI at the national level on a bilateral basis, and the resulting legal, financial and research challenges that are emerging, highlighting a complex and patchy policy international policy arena.

Embedded within DSI is the traditional knowledge (TK) of those who bred the plants whose seed are being digitised (González Merino 2022). A central question, therefore, is whether TK can be decoupled from underlying genomic information (Rourke 2018). Identifying links to TK within sequences is challenging given that genetic resources are drawn from multiple sources and organisms, may include repetitive stretches of DSI, typically do not include provenance data, and may change during the research process (Laird et al. 2018; Aubry 2019; Aubry et al. 2021; Wynberg et al. 2021).

Nevertheless, the growth of DSI is unstoppable. There are already more than 1500 publicly accessible biological databases. The largest databases are part of the International Nucleotide Sequence Database Collaboration (INSDC), comprising 1.5 billion genetic sequences (Scholz et al. 2020). Developments in genomics and molecular biology are also likely to enhance the characterisation and evaluation of wild genetic resources and landraces, and hence the quantity of DSI that is publicly available. Many of these DSI databases are currently held in open-access formats (Laird et al. 2020); however, the legal protection to restrict the mining and private profiteering and further enclosure of new products developed from their contents does not yet exist. A significant amount of DSI

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[2] The smallest assembly that can perform a specified function, such as a basic biological circuit (e.g. an on–off switch) or the translation of a particular protein coding sequence (Rourke 2021).

is privately held, and since the benefit-sharing relating to DSI is difficult to identify and hindered by a lack of clear international governance and legislation, some authors have identified a reluctance to make privately generated DSI publicly and freely available (Cowell et al. 2021).

For countries that provide PGRFA, not including DSI within the scope of the CBD, NP and Plant Treaty presents an intolerable 'digital loophole' (ETC 2010). This legal loophole allows users (states and private companies) of PGRFA to avoid benefit-sharing obligations by synthesising genes (and elements) of interest by generating and using publicly accessible genetic sequence data rather than engaging with authorised providers of physical genetic resources to enter into an ABS agreement with the provider's prior informed consent (Rourke 2021). The current enclosure of DSI in the sovereign domain of the nation state represents a threat to the professed open-access principles of modern science, and a barrier to the latest synthetic biology research (Rourke 2021).

Appropriationism and substitutionism: analysing the evolving types of seed enclosures

Throughout history, agriculture has always been the sector of the economy spearheading the automation of labour in search of consistency, control over natural (including human) factors and processing conditions to maximise homogeneity and cost reductions (Friedman and McMichael 1989). For centuries, industrial capital has relentlessly attempted to transform the agri-food system as a unified whole, and failing overall; instead, interventions have been taking place in specific points of the system. Goodman et al. theorised these interventions into two categories: appropriationism and substitutionism. Appropriationist capitals focused on production and primary transformation processes of crops, while substitutionism was initially used post farm gate in food manufacture stages (Goodman et al. 1987). Industrial appropriationism of the rural labour process started with instruments of production replacing human and animal energy. Nowadays, however, mechanical dimensions are increasingly and rapidly converging with digital and biochemical innovations with the aim of controlling both labour and biological production processes (Montenegro de Wit 2021; Hassoun et al. 2022). This control engineers the dependence on inputs and technologies that disrupt and simplify natural cycles with severe externalised costs and impacts (Sustainable Food Trust 2017). Linked to appropriationism, substitutionism refers to industrial processes that replace natural products with easy-to-manufacture and control alternatives, such as replacing butter with margarine (Goodman et al. 1987).

The increasing adoption of industrial approaches and factory-like methods 'free' food production from the unpredictability and inconsistencies of natural processes that hinder the economic prospects of many agricultural commodities (Goodman et al. 1987). These days, appropriationist and substitutionist practices take place in both primary and manufacturing stages, such as in underground hydroponic systems using LED technology, offering complete control over growing conditions (Growing Underground 2022). This growth of closed-loop aquaponics systems in urban environments not only reflects appropriation of natural cycles by industrial methods and conditions, but also offers an example of substitutionism processes through the replacement of soil by liquid solutions. Another type of laboratory appropriation is the growing trend of *in vitro* cultivation of animal cells to produce meat, completely replacing animals and outdoor-occurring processes (Stephens et al. 2018).

The control over and appropriation of elements of natural environments labelled as resources, such us woods, land and water – all key to food production – began with physical processes of enclosure, with land enclosures taking placefirst (Heller 1998). Private enclosures of common land by the aristocracy, combined with the First and Second IRs' thirst for cheap labour, pushed people off the land into factories from the late eighteenth century, a process still ongoing in many countries through contemporary land grabs (Polanyi 1965; Araghi 2009; Fraser 2019). In the realm of seed, Kloppenburg (1998) and Montenegro de Wit (2016) have carefully documented and analysed historical and more recent processes of seed privatisation of both cultivated crops and crop wild relatives through the Marxist lens of primitive accumulation. Replacing farmers and landless agricultural workers is an ongoing historical trend that has evolved alongside the technologies of the different IRs. First, animal labour was replaced by machines. More recently, human labour in agriculture, processing and distribution, considered a costly and difficult-to-control element of the production cycle, is gradually being replaced, aiming for full removal or at least minimisation in the production equation (The Guardian 2022). In the words of Frank Wilczek, professor of physics at Massachusetts Institute of Technology and Nobel Prize winner, machines 'have a very good duty cycle. They don't need care and feeding and, most importantly, they don't die' (2019).

Next, building on the concept of enclosure, I analyse how through mechanisms of appropriation and substitution, five interwoven types of seed enclosures – logistical, technological, legal, financial, social and technological – have been evolving over the last century.

Logistical enclosures

For millennia, very few (or no) legal initiatives were designed to exclude access to PGRFA (Kloppenburg 1988; Halewood 2013). Plant genetic resources were widely and freely dispersed around the world, and it was difficult to exclude others' access to, and use of, such seed. The biophysical units of PGRFA stock can be extremely small and portable (e.g. a seed or a plant cutting). One only needs a few viable seeds to be able to carry away the full informational and biophysical components of the genetic resources of a particular crop variety or species. Thus, since seed was hard to enclose, andinvestment in plant breeding came almost exclusively from the public sector until the 1950s, seeds and improved varieties were considered public goods (Halewood 2013). Thus, there was also little to no concern about their conservation, until the 1960s, when concerns started to be expressed about the replacement of farmers' varieties with green revolution cultivars. From the late 1960s onwards, coordinated efforts at the international level (under the auspices of the Food and Agriculture Organisation (FAO) and the Consultative Group for International Agricultural Research (CGIAR) centres), were directed towards the collection and conservation of PGRFA *ex situ* with the aim of increasing its availability through collections (Engels and Ebert 2021), opening up a physical enclosure and distancing of seeds from their places and communities of provenance and evolution. Now that a vast diversity of PGR of many crops has been centralised in *ex situ* collections – including PGRFA of crops and forages that may no longer exist *in* *situ* – those *ex situ* PGRFA have become much more (potentially) excludable, i.e. it is now easier to restrict access to them (Wynberg et al. 2021).

National gene banks usually supply samples to researchers and breeders upon request, though they often do not distribute directly to farmers. Private companies generally do not make any of their collections publicly available. It is also necessary to consider potential practical limitations on access to *in situ* PGRFA (Wynberg et al. 2021). *In situ* PGRFA diversity often exists in marginal farmlands or 'in the wild' (in crop wild relatives) and can most practically be reached by foreign scientists through formal collecting missions, relying on the expertise of national scientists or local farmers to locate the plant populations concerned. Without the cooperation of national and local authorities and farmers, the *de facto* availability of those resources can also be limited.

Legal enclosures

Centuries-old seed saving skills and practices have been increasingly lost and criminalised (Kloppenburg 1988; RtFaNW 2016; Wattnem 2016; Aceituno-Mata et al. 2017). International law did not start to become interested in plant genetic resources in the 1960s, when the Green Revolution was spreading its new methods and techniques. Subject to a few exceptions in the form of national or colonial governments issuing edicts against exporting the planting material of particular species, plant genetic resources had also been largely ignored by national law (Fowler 2000). In 1961 however, the International Union for the Protection of New Varieties of Plants (UPOV) became the official intergovernmental body for governing PGRFA. Since its formation, this body has worked exclusively and explicitly for the privatisation of seeds around the world by imposing intellectual property rights on plant varieties. Member states that join the UPOV Convention are obliged to incorporate it into their national law. The UPOV Convention was revised in 1972, 1978 and 1991, each new version strengthening the rights of dominant commercial breeders and increasingly restricting what smaller growers can do with the seeds (GRAIN 2015). The 1991 revision was particularly controversial as it severely reducedthe right of farmers to save seeds in order to "safeguard the legitimate interests of the breeder" (UPOV 1991; Peschard, 2016). The UPOV convention has gradually continued to bolster the protection of plant breeders' rights (Wynberg et al. 2021).

In 1983, the FAO Council adopted the non-legally binding International Undertaking on PGRFA, proclaiming PGRFA as heritage of mankind that should be available without restriction (FAO 1983). However, countries in favour of private appropriation of subsets of PGRFA through plant variety protection laws refused to endorse the International Undertaking (Kloppenburg and Kleinman 1987). In 1989, FAO recognised the primacy of plant variety protection law over the common heritage principle. The Uruguay Round of the General Agreement on Tariffs and Trade (GATT) negotiations triggered a new FAO Council resolution in 1991, recognising nations' sovereign rights over their genetic resources; these national rights were later amplified in the CBD in1993. Obligations for tracking, reporting and enforcing access and benefit-sharing agreements were then adopted in the form of the NP in 2010 (Frison 2018). For agriculture, the ITPGRFA and its MLS came into force in 2004. The worldwide proliferation of national and regional intellectual property laws constraining seed rights has been just as labyrinthine, including patent laws, plant variety protection laws, contractual restrictions accompanying seed sales and bilaterally oriented access and benefit-sharing laws (see Halewood 2013 for a detailed description of each of these legal mechanisms).

To avoid some of the complicated contracting arrangements required by the CBD and NP, the Plant Treaty has a Standard Material Transfer Agreement (SMTA) that has been used to distribute over 6.3 million samples as of mid-June 2022 (FAO 2022). According to the agreement, if parties incorporate MLS material in a new PGRFA product, and do not allow others (through technological or legal restrictions) to use it for further plant breeding or research, the recipient must pay 1.1 percent of gross sales to an international benefit sharing fund. However, contributions made by users of PGRFA to the benefit-sharing fund established under the treaty have been disappointing (FAO 2019b). While the rate of benefit-sharing instances has been low, the rise of patents has not stopped (No Patents on Seed 2020). Patents already cover everything from 'low pungency' onions to 'brilliant white' cauliflower to Carlsberg hops for beer, with seed companies rushing to claim what territory remains (Hamilton 2014; No Patents on Seeds 2020).

More recently, the recognition of farmers' contribution to diversity, and of seeds as shared heritage of humanity that must be preserved, was included in the United Nations Declaration on the Rights of Peasants (UNDROP 2018). The Declaration aspires for individual and collective rights to be granted to local communities for land, seed and natural resources and for research priorities to be both defined and implemented by farmers. Even though the Declaration is not legally binding, it took 17 years of negotiation to achieve it. One reason for this long delay and process of negotiation was that industrialised countries rejected the Declaration as it challenged the international property law regime, especially with regards to intellectual property rights over seeds (Claeys and Edelman 2020).

Financial enclosures

Just four corporations – DowDuPont/Corteva, ChemChina-Syngenta, Bayer-Monsanto and BASF – controlled over 60 percent of the total value of purchased seeds in 2014, excluding farm-saved seed but including public commercial varieties, for around US$52 billion (Peschard and Randeria 2020b). Currently, as a result of large mergers, the leading pesticide companies also dominate the world market for commercial seeds and traits (ETC 2022).

Facilitated and strengthened by the legal framework, the privatisation of seed has created new financial enclosures. The investment needed to access hybrid seeds and patented varieties, and, furthermore, to develop new ones, has developed capital enclosures in which only actors with the necessary funds can participate. Gene editing technologies and gene sequencing technologies, while increasingly cheaper than before, are still only affordable by very few players in the agrifood industry.

As well as severe reductions in farmers' rights, proprietary seeds drastically reduce biodiversity too, since the intellectual property (IP) architecture to which they belong and biodiversity are complete opposites (Kloppenburg 1988 [2004]). Cultivated diversity can serve as a buffer against diseases or environmental changes, but the legal obligation farmers face to use registered seeds, in some cases to access subsidies, creates dependence on multinationals, and it homogenises global crops. Uniformity of monocultures of monovarieties is a growing threat, especially as access to many varieties has become restricted, reducing the diversity of crops and diets.

Furthermore, market-driven forces for seed selection (e.g. storage ability and uniformity) are not often aligned to local growing needs (e.g. adaptation to local climate). But market forces run the seed world. Varieties that encode capitalist values, i.e. that prioritise production over survival, are being developed, intentionally ignoring the urgent need to mitigate and adapt to the climate emergency (Casagrande et al. 2017; Silva 2021). The improvement of a plant variety is a research process that requires an average of between 10 and 15 years, and an economic investment of between two and three million euros. In Europe alone, the seed industry accounts for approximately 7000 million euros' worth of trade, comprising a total of 7200 seed companies employing more than 50,000 people (ISF 2022). The tiny, humble seed is big business.

Social enclosures

Famers' access to gene banks and connections to broader, national and internationally distributed forms of PGRFA-related innovation are generally very weak to non-existent, with some notable exceptions in the form of participatory breeding projects, and recent efforts to develop more active two-way linkages between community seedbanks and national gene banks and participatory monitoring of climate changes and the performance of varieties (Halewood 2013).

Almost the totality of the materials in the MLS are in *ex situ* collections. In addition, most new deposits of PGRFA to the CGIAR gene banks are duplicates of materials already included in national *ex situ* collections. Very little 'new' PGRFA deposited in internationally available collections – new in the sense that it was not previously included in the MLS – was recently collected from *in situ* conditions. And subject to only one exception – the potato park in Peru – no notifications have been shared about PGRFA that remains in *in situ* conditions as being included in the MLS (Halewood 2013). Despite farmers' contribution to maintaining and creating the biodiversity of PGRFA being recognised in international treaties, there is a process of erasing their individual contributions. The name of the farmer from whom material is collected is usually not part of the records that collectors and gene banks maintain about the materials in their collections (Halewood 2013; Wynberg et al. 2021). By the time they are formally part of a gene bank collections, the connection back to the farmer from whom the PGRFA was originally collected is completely lost. SMTAs are agreed between organisations, not farmers. The social and cultural realities of farmers are often far removed from *ex situ* collections, global agreements and more currently, DSI databases, as will be discussed later.

The historical gender dimension of seed stewardship should also be acknowledged. Throughout history, seed saving was an activity carried out and managed by women, and still is in many countries today. It is another area of society in which women's power has been diminished (Swiderska 2018; Traoré 2018).

Moreover, farmers and scientists have very different worldviews and knowledge systems (Stirling 2011; Montenegro de Wit 2016) and ways of knowing about agrobiodiversity (Cremaschi and van Zwanenberg 2020). Farmers who do not align with the legal framework are considered uncivil or illegal. Sullivan and colleagues have unravelled this claim in their study of social movements (Sullivan, Spicer, and Böhm 2011). They analysed how practices or organisations gaining significance in contesting and escaping the structuring enclosures of dominant regimes become labeled as 'uncivil', when, in fact, many would argue the 'uncivil' are the enablers of the status quo.

Technological enclosures

Each IR has introduced its own type of enclosures based on the technologies available at the time. In the case of seed, parallel to the emergence of *ex situ* collections, a systematic introduction of technological restrictions on access to, and use of, PGRFA came in the form of hybridised corn, in the early part of the twentieth century. A wide range of other hybrid crops have been developed since, opening a commercial market for hybrid seeds, with companies keeping the inbred parental lines as trade secrets, and often subjecting the varieties to plant variety protection (Halewood 2013; Kloppenburg 2014). Farmers cannot save the seed of hybrid crops, becoming commercially dependenton seed suppliers. New gene editing technologies have even further removed breeding from farmers' realities and control (Montenegro de Wit 2021).

These technical lab enclosures have progressed into the digital dimension of the Fourth IR. Seeds have entered the digital arena with technological advancements such synthetic biology and gene sequencing (Cabrera Medaglia 2020). The modelling, simulation and visualisation of biological processes in computers has been termed '*in silico*', referring to any application of any computer-based technologies – algorithms, systems and data mining or analysis. *In silico* is now considered a new mode of seed conservation similar to the physical *in situ* and *ex situ* methods. New academic journals on *in silico* plants are now being published (*in silico Plants* 2022).

In conjunction, other aspects of seed regulation, such as certifications and the distinct, uniform and stable criteria required to register varieties in official registers, are examples of transversal mechanisms that convey different enclosures: legal, financial and technological.

Next, I argue how, in the case of seed, two new domino effects of Fourth IR technology, dematerialisation and fragmentation of genetic materials, are generating new types of digital enclosures, resulting in serious global governance challenges for PGRFA.

Dematerialisation and fragmentation of seeds: the rise of the digital industrial engineering food regime

Seeds have a tripartite character: material components (the physical seeds), cultural aspects (the past and present contribution of humans to breeding and associated traditions) and informational aspects (DNA sequences, knowledge regarding breeding and cultivation) (Sievers-Glotzbach et al. 2020). Digitising genetic material distances us from it, as it no longer has a physical presence. Genetic information can be replicated and used without movement of, or access to, physical specimens, making it easier for companies to accumulate than material seeds (Cowell et al. 2021). Data are 'the new cash crop' (Fraser 2019; Fraser 2020). The dematerialisation of seeds increases their excludability as a good, speeding up their conversion from common to private goods.

Furthermore, in DSI databases, farmers' relations, knowledge and contributions to seed get lost in the digitisation process (Traoré 2018; Nawaz, Satterfield, and Hagerman 2021).

Combined with dematerialisation, the ability to fragment genetic resources and to apply industrial engineering methods to PGRFA is fast developing. Synthetic biology applies engineering principles to biology, and is heavily dependent on genetic resources data, particularly genetic sequence data (Cai et al. 2020; Rourke 2021). The field of plant molecular farming has also emerged as a novel area of research at the intersection between plant biotechnology and industrial bioengineering (Peyret, Brown, and Lomonossoff 2019). The use of computing engineering language when talking about digitalised seed material, such as coding, editing, precision and devices, is an indication that the food regime is now a digital industrial engineering food regime pursuing a fordist model for synthetic biology applications. The fact that Github[3] has built its physical back-up next to the Seed Vault in Svalbard seems to depict a future in which food sovereignty will be intrinsically linked to data and technology sovereignty struggles (Vaughan 2020).

The poster boy of fragmentation of PGRFA is the gene conceived as a well-defined, predictable and determinant unit. However, abundant biological evidence highlighting how genes do not exist as clear entities is piling up, indicating how we are only starting to learn about the key importance of epigenetics, variability, plasticity and emergent properties (Rossi 2013; Bonneuil et al. 2014; Rheinberger and Müller-Wille 2018). The fact that genes are context dependent should be a sufficient scientific and legal argument against their patentability. Nevertheless, the idea of determinant genes is widely used to share uncomplicated stories of predictable traits, and to generate expectations and business (Rheinberger and Müller-Wille 2018; Nawaz, Satterfield, and Hagerman 2021). The gene has become a countable and an accountable body. This focus on quantifiable aspects is a common sign of the quantophrenia that has reached other areas of the food system, resulting in the simplistic reductionism of complex socio-ecological systems (Ajates 2020).

Furthermore, as Nawaz and colleagues have pointed out, genes can only be patented once they have been isolated, extracted from an organism, and inserted in another. It is this fragmentation of information from the physical matter that has transformed genes into tradeable, sellable and patentable entities, and, thus, susceptible of being enclosed (Nawaz, Satterfield, and Hagerman 2021). The conceptualisation and assetisation of genes as a stand-alone units with on–off switches allows the 'translation' of life into the familiar binary language of the Fourht IR discourse and technologies. Shaped by the dictates of political economy, researchers pursue metaphors, topics and methods that reproduce logics of capital accumulation, while shedding in the process other forms and meanings of life, thus narrowing diversity (Fullilove 2018). Fragmentation is also palpable in the legislative framework for PGRFA. For example, seed marketing, farmers' rights and plant health regulation are all related dimensions; however, each aspect has separate legislation, with multiple institutions and legal misalignments involved (Aubry et al. 2021).

The analysis of these series of interrelated enclosures shows that the grab of resources by the industrial regime is not new to the food system, and not new to seed. Many

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[3] Github is the world's most widely used open-source software host and it has been owned by Microsoft since 2018.

national gene banks were stocked with hundreds of thousands of accessions collected from former colonies without an officially mandated benefit to the communities from which they were originally gathered, and without globally coordinated agreements regarding benefit sharing (von Wettberg and Khoury 2020). DSI is a new tool of the latest IR, and based on the reach and speed of its growth and potential implications for food and agriculture and beyond, there is an urgent need to consider how the current legal framework should deal with DSI and break the exploitation cycle (Ambler et al. 2021).

The next section discusses the OSS model, which has been emerging in the realm of physical seeds. I present evidence of how an open-source framework is well positioned to be applied in the context of the Fourth IR, as it requires arrangements that operate across digital, physical and biological spheres.

The potential of OSS for seed sovereignty

The confluence of seed enclosures has brought about a series of systemic impacts. Regarding its governance, the current model has become an elite system that requires an extraordinary level of legal, scientific and technological skills and resources, excluding or hindering countries with fewer resources, and the actual users and stewards of cultivated diversity, i.e. farmers. Even many sequence-using scientists are unfamiliar with the international political processes of PGRF and the ongoing DSI debates (Rohden and Scholz 2021).

In conjunction with agricultural impacts, these enclosures have imposed uniformity in agriculture, a growing threat that also increases our vulnerability to the climate change emergency due to and fuelling biodiversity loss (FAO 2019a). Proprietary seed packages often come with a complementary set of artificial inputs that perpetuate intensive methods. Public health impacts, related to agricultural ones, also worsen, e.g. lower harvests get translated into fluctuating food security; pesticide traces in food are increasing, and loss of natural biodiversity also translates into reduced diversity in diets and loss of nutrients in crops (Fanzo et al. 2018). Impacts on biodiversity have been documented too, in relation to the ongoing loss of existing cultivated varieties, and intensive farming impacts on wildlife and wild varieties of domestic crops (Willett et al. 2019). Finally, socioeconomic impacts include subsidy barriers and dependency on external inputs and market concentration; distrust within farming communities (e.g. cross-farm contamination of patented varieties) and loss of cultural heritage (Phillips 2016).

In the last 50 years, as a result of advances in applied biosciences and the promotion of exclusive legal protections, an increasing proportion of PGRFA have been subject to various forms of capture (Kloppenburg 1998). As such, they have been converted into appropriated, private goods. The ABS regulations that were designed for simplistic conceptions of bioprospecting activities are now having to meet the challenge of regulating new scientific methods that result in a level of abstraction of PGRFA that the negotiators of the CBD and Plant Treaty could never have imagined (Wynberg and Laird, 2018). The digitalisation of bioprospecting activities – the process of discovering and commercialising biological resources – has alegal 'biopiracy' allowed by the current DSI legal vacuum.

At the same time as the governance framework and new technological advancements have been developing, there has been a rise in global initiatives determined to denounce and raise awareness of seed privatisation (Peschard and Randeria 2020b) and to re-skill growers in the art of seed saving (Gaia Foundation 2021). The attempts to defend farmers' right to seed follow 40 years of struggle over the development of the legal framework, a struggle that did not win over biopiracy and the primacy of intellectual property rights, and that now is entering the digital world. I argue, as seed appropriation and enclosures evolve in the Fourth IR, seed social movements also need to expand more urgently to the digital realm. Novel disruptive technologies have created a much more complex context for seeds, far removed from the reality of food growers. As our societies and economies become more driven by data and information, the governance of information is increasingly important (Rohden and Scholz 2021). In this context, building on digital commons and open-source software movements (Kloppenburg 2014; Kotschi and Horneburg 2018; Moeller and Pedersen 2018), which in turn built on the idea of the commons and the cooperative movement that originated in food about two centuries ago (Ajates Gonzalez, 2017); Scholz and Schneider 2017), the concept of OSS has been unfolding over the last decade, raising awareness of seed struggles in legal and epistemic arenas (Kloppenburg 2014; Kotschi and Horneburg 2018). Several initiatives exist across the world. The Open Source Seed Initiative in the United States was the first one to formalise and is still ongoing (Kloppenburg 2014; Montenegro de Wit 2017). More OSS initiatives followed in othercountries, including Argentina (Cremaschi and van Zwanenberg 2020; Bioleft 2022), Germany (Open Source Seeds), Italy (Rete Semi Rurali 2022); Kenya (Seed Savers Network Kenya 2021) and the Philippines (MASIPAG 2022). These initiatives along with a wider network of organisations and individuals – farmers, seed keepers, plant breeders, researchersand activists decided to join efforts and form the Global Coalition of Open Source Seed Initiatives (GOSSI), an international networkdeveloping and promoting OSS and participatory breeding (GOSSI 2022).

GOSSI has developed and adopted a set of core principles applicable to all OSS projects that can be adapted to local contexts. It has been compared to 'Linux for lettuce' (Hamilton 2014). OSS varieties can be bought, but cannot be privatised. Some of Monsanto's corn breeders called OSSI seeds 'too contagious to touch' (Lawn 2016). As Kloppenburg has highlighted, an OSS label on a seed package not only states the intentions and rights of the farmer or breeder who developed the variety, but, just as importantly, raises awareness of this hidden battle with consumers. It prods

> the uninformed to question why seeds would *not* be freely exchanged – why this pledge was even necessary. It would inspire those who already knew the issues of intellectual property to care more and spread the word. As the seed multiplied, so would the message. With three simple sentences, OSSI would propagate participants in the new movement like seedlings. They would breed resistance. [… The] idea is to use 'the master's tools' of intellectual property, but in ways the master never intended: to create and enforce an ethic of sharing. (Kloppenburg in Hamilton 2014, emphasis in the original).

This spread of the open access and commons discourse thus has a double effect: 'it has helped identify new commons and, in providing a new public discourse, it has helped develop these commons by enabling people to see them as commons' (Bollier 2007:3).

Table 1. Multilevel challenges facing seed systems in the Fourth Industrial Revolution, and potential solutions that open-source seed systems (OSSS) can offer.

Seed system challenge	Potential solutions offered by OSSS
Logistic challenges	
A physical global PGRFA commons would be ‘heavy’, expensive, complex and slow to evolve in comparison to digital information commons and open-source software.	With the growth of DSI, the parallelism with open-source software and OSS is stronger, opening new pathways for an OSSS licensing framework for DSI.
A vast diversity of PGRFA has been centralised in *ex situ* collections – including PGRFA of crops and forages that may no longer exist *in situ* – becoming much more (potentially) excludable.	This development, while a risk for the evolution of biodiversity, opens up the possibilities for excluding certain profiteering uses of PGRFA by licensing PGRFAs in *ex situ* collections as OS.
Unlike other common pool resources such as water and land, seeds reproduce more the more times people use them. Thus, the principles developed to govern non-reproductive common pool resources need to be adjusted before being applied to seed systems.	OSS encourages seed and its progeny to be shared and reproduced without IPR restrictions.
Only 17% of NSD identifies the country of origin, and it comes from US, China, Canada and Japan, not countries of the Global South as expected (Rohden and Scholz 2021). A DSI benefit-sharing scheme linked to provenance thus would, ironically, provide substantial benefits to the Global North at present. Similarly, The Parts Agenda research makes ascertaining the origin of bioparts a complex logistical and legal challenge.	An OSSS model would solve the current imbalance on provenance data which unequally affects low- and middle-income countries. Furthermore, ascertaining the origin of biobricks would no longer be relevant if they were not considered patentable.
Financial challenges	
The returns obtained from the use of regulated PGRFA have been disappointing (FAO 2019b). Even if the rules are adhered to, the returns on a ‘blockbuster invention’, which are uncommon, would still be meagre (Vogel et al. 2021). Bilateral agreements outstrip the expected benefits, and completed ones were declared ‘successes’ simply because they were concluded (Vogel et al. 2021).	The underlying issue is that biodiversity should not be funded only by the ABS system (Voget et al. 2021). OSS allows us to reimagine potential financial models for biodiversity and breeding programmes.
While the open character of DSI databases is common, the capacities and resources of companies, researchers and more generally countries in the Global North and South create critical differences and disadvantages for the latter. Open access is not enough; more support is required to overcome the digital divide (Rick and van Hintum 2020).	While OSSS would not solve centuries-long global inequalities, it would buy low and middle income countries time to develop their research and technological capacities and close the digital divide, by avoiding, or at least decelerating, the privatisation process of PGRFA. Open-source arrangements could see materials freely available and widely exchanged, but ‘protected from appropriation by those who would monopolise them’ (Kloppenburg 2010, 367).
The value of DSI is substantially greater when spatial, phenotypic, demographic and biochemical information is available for the same sample and can normally only be put to practical use if living specimens of close relatives can be accessed. The value for individual physical samples is increased when linked to DSI (Cowell et al. 2021).	OSS would allow open access to a wide range of data if integrated with *in silico*, *ex situ* and *in situ* PGRFA.
Approximately 90–95% of all genetic resources used today in plant breeding are modern varieties derived from private gene banks. Only the remaining 5–10% represents landraces or wild relatives, *but there is growing interest and investment in utilising crop wild relatives and farmer varieties to explore their potential for adapting to climate change* (Wynberg et al. 2021). *Furthermore, there is increasing consumer demand for novel and less known varieties*.	It is a timely moment to apply OSS mechanisms to protect unpatented farmer varieties before commercial interests enclose them, and foster participatory projects that share the benefits along the seed value chain.
Technological challenges	
Digital copies of seed can be easily and quickly multiplied, unlike physical common-pool resources; thus, the design principles developed for the latter need to be adjusted before applying them to digital commons.	The open-source seed movement pays attention to the processes, types and effects of exclusion from DSI, which are an important step in designing principles for digital data and information commons.
OSS initiatives have so far focused on physical seeds. DSI is contributing to the dematerialisation of seeds.	

(*Continued*)

Table 1. Continued.

Seed system challenge	Potential solutions offered by OSSS
	DSI opens up an opportunity to apply more directly the models, lessons and best practice of the OS software community.
Seed producers and breeders are not visible in food systems, not even in Alternative Food Networks. DSI developments make their role in securing seed biodiversity even more invisible.	The OSS movement offers them visibility and inclusion in the more public struggles of the food system, and linkages with the related movements of the digital commons, open cooperativism and OS software. This inclusion highlights the common denominator of concentration of power and loss of diversity. OSS can provide visibility among consumers and seed buyers.
Only a few players have the technological capacity to generate DSI data. Small farmers and small breeders do not have the resources to create DSI copies of their own varieties.	OSS offers a framework to protect seed material, in both physical and digital formats. Developing an OSS framework now for DSI can future-proof the seed sovereignty movement for a not-so-distant future in which NGOs and small-scale breeders' networks such as Seeds for All might be able to afford their own digital sequencing.
Legal challenges	
Currently, genetic resources as *res nullius*, that is, property of no one, and thus is susceptible of appropriation (Vogel et al. 2021).	The OS framework allows a disruptive change in the legal playing field by converting seeds into *res communis*, i.e. the property of everyone.
The current legal IPR framework has been failing to address the fact that crop diversity continues to be lost (both from *in situ* and *ex situ* collections).	OSS would allow the focus to be placed on conservation of cultivated diversity.
The current legal framework is not future-proof for novel scientific developments and offers legal loopholes that allow PGRFA to free ride the system.	OSS and copyleft provide fewer loopholes and also enable the development of a future-proof framework by focusing on enhancing diversity instead of the patent system.
Having the physical seed alone is not enough. Given the fact that the many DSI databases are currently open and that techniques such as CRISPR/Cas9 are largely publicly funded, the logistical, knowledge and economic exclusions built into the system make their potential to democratise and protect biodiversity a very unlikely outcome (Montenegro de Wit 2021). The patent system breeds more patents, perpetuating a system of legal enclosures, as applications for patents are only checked for similarity against other patented PGRFA – not for similarity against non-registered traditional varieties.	OS offers a legal protection to navigate the physical and digital systems of management and regulation that dictate what farmers are or are not allowed to do. OSS would allow protection while sharing, avoiding the need for further enclosures. A compromise might lie in establishing prior art, i.e. by documenting relevant PGRFA and associated traditional knowledge in such a way that it cannot be made subject to IPRs in its existing form.
Social challenges	
Seed banks were the response to industrialised seeds. Now moving to DSI and the digital sphere, seed activism is more complex, and far removed from the reality of farmers. A new mode of resistance is needed.	OSS offers a proactive and more future-proof resistance mechanism, avoiding a lack of action against challenges perceived as too complex. It offers farmers a new way to take part in policy debates. OSS can raise awareness of legal seed issues amongst consumers and other seed buyers.
New laboratory-based breeding techniques are, in their current trend, being design to appropriate breeding processes, and substitute breeders.	OSS participatory breeding approaches that take into account criteria from different types of stakeholders, such as agroecological farmers, chefs, consumers, etc., are essential to avoid further distancing between breeding activities and growers and consumers.
The focus on IPRs has meant the erosion of principles of common heritage in farming communities where land and other natural resources are communally owned, seed is exchanged or shared, provenance is ambiguous, new varieties are shared and natural and artificial selection are intertwined.	OS models offer a recognition of the values of the commons, sharing and collective stewarding that have been eroded and buried under dominant discourses of property, enclosures and exclusions.
Although farmers' contributions to the development and conservation of PGRFA are collectively recognised by the ITPGRFA (article 9), the contributions of individual farmers to the generation of PGRFA is generally invisible.	OSS can offer an attribution framework and visibility for farmers and breeders. Current OSS initiatives avoid heirlooms varieties (unless not defined before) and varieties in circulation to avoid potential appropriation.

(*Continued*)

Table 1. Continued.

Seed system challenge	Potential solutions offered by OSSS
Additionally, the process of digitisation increases the risk of misappropriation of genetic resources and associated TK.	OSS is advised for new varieties, novel lines or populations. Community data trusts could move the OSS licence from the individual to the community. OSS can also serve as a tool to empower a new set of breeders.
Farmers and breeders who do not align to regulatory frameworks face legal charges and/or being labelled uncivil (Sullivan, Spicer, and Böhm 2011).	OS offers a legal framework for farmers and breeders who wish to focus on their production activity without legal concerns.
Integrating ISD into the current ABS system would end up running counter to the principles of open science promoted by the European Commission, UNESCO and other international institutions.	OSS can be framed in the wider global efforts for open-science responsible research and innovation and public participation in science.

Since PGRFA are the products of complex interactions between crop breeding systems and natural and human selection, they occupy a middle ground between natural resources and human-made cultural resources (Halewood 2013). Open source (OS) principles are transferable enough to be effective in both spheres. OSS initiatives are currently focused on labelling physical seed packages with an open-source pledge or licence. However, as charted in the previous section, the digitisation of seed material opens up new urgent challenges for seed sovereignty (Muzurakis 2019). GOSSI has adopted a set of core principles to which all open-source seed projects adhere, which could be adapted and applied to DSI: (a) anyone may freely grow, save, propagate and breed OSS; (b) recipients may not privatise OSS or its progeny through exclusive IPR or other use restrictions; (c) recipients of OSS must assign the same rights and obligations to subsequent recipients; (d) the breeder of OSS shall be recognised through attribution of credit; and (e) benefits shall be shared all along the seed value chain (GOSSI 2022).

The OSS model, combining the principles of the commons with the legal protection of the copyleft licence (Fredriksson 2021), offers a future-proof framework for resisting the challenges posed by the Fourth IR. Additionally, it is a timely opportunity to gain support for open developments encompassed in wider movements for open science, citizen science and responsible science (Strasser et al. 2019; Michael 2020; UNESCO 2021). Open science should involve the whole process of generating new knowledge and new varieties, as well as – instead of just – DSI.

Table 1 I documents how seed movements are at a crossroads to adapt to the new challenges facing the management, development and protection of biodiversity for food and agriculture in the digital sphere, while also continuing to resist losses in the physical sphere. The table summarises the multilevel challenges facing seed systems in the Fourth IR, mapping the potential solutions that open-source seed systems (OSSS) can offer across five dimensions of enclosures previously discussed: logistical, financial, legal, social and technological.

Perceived limitations to OSSS: an opportunity to rethink a new governance framework for conservation and cultivated diversity stewardship

There are some perceived limitations to OSSS, mainly around investment recovery and profitability (FAO 2022). The FAO's recent assessment of OSSS initiatives in Kenya, Uganda and United Republic of Tanzania identified many achievements on capacity building, partnerships, crowdsourcing of landraces and the use of community seed banks, however, the evaluation questioned if the BSF should invest in the OSSS component of the project as it was deemed not profitable and not compatible with the MLS of ABS. A solution that has been put forward to solve the DSI debate is the open-access-based proposal for avoiding complex benefit-sharing obligations known as 'bounded openness' (Vogel et al. 2011; Vogel et al. 2021). This approach involves the creation of a centralised institution to encourage provider countries to conserve biodiversity and associated knowledge. In this model, benefits are shared freely and openly – until they generate revenue, at which point benefit-sharing obligations are triggered. The model requires that patent or other property right applications are set up to request disclosure of origin. A version of such an approach based around the idea of a 'subscription model' has been proposed to solve the DSI problem but so far has not been accepted (Oldham 2020). In the current financial context, an OSS model for DSI, by not allowing IPR restrictions on either OSS or its progeny, would create a lower return on investment for breeder seed companies (Louwaars 2019), which in turn could result in fewer payments into the CBD common fund. Taking into account that those contributions have been disappointing to date anyway (FAO 2019b), there is a need to highlight the underlying limitation explicit in the CBD, i.e. that biodiversity conservation is effectively expected to pay for itself (Laird et al. 2020). Fairer and more effective models for financing conservation and breeding must be found as all evidence suggests current ones are only working for some dominant players. Some OSS initiatives have already started to explore new financing avenues (Kotschi and Wirz 2015; Kasveista 2022; Colley et al. 2022; Kotschi et al. 2022).

Another limitation to the OSS model refers to how, by operating through the licence system, it might be perceived as contradicting the commons perspective (Louwaars 2019). These is a limitation only if considered through the lens of the current dominant legal and financial system of PGRFA and biodiversity governance. The ABS is still framed within the same private ownership of life regime. The current system and the bounded openness proposal might be based on open data sets, but the data and, thus, their associated PGRFA are not protected from appropriation, as legal enclosures of the material are allowed after one productive cycle. Currently, genetic resources as considered *res nullius* – that is, property of no one – and thus are susceptible to appropriation (Vogel et al. 2021). The OSS and copyleft licence offer a legal protection that allows a disruptive change in the legal playing field by converting seeds into *res communis*, i.e. the property of everyone.

Because some technologies have abetted industrialisation, consolidation and global neo-liberalisation of food and agriculture, technology may be categorically dismissed as a potentially productive analytical and practical entry point for work on sustainability transitions for seed systems, and more generally for food and agriculture. Critical agrarian studies have generally viewed capital-intensive technologies as contributing to unsustainable and unfair models of management of natural commons and food production unsustainability (Hinrichs 2014; Montenegro de Wit 2021). However, the success of open-source software and digital commons offers a hopeful glimpse of the potential to apply open-source principles to seed systems. The OSS mechanism offers the opportunity to breed resistance, both literally and metaphorically, and to use the tools of the dominant system to create and enforce an ethic of sharing (Kloppenburg in Hamilton 2014). This industrious subversion of the tools of powerful actors can enable those at the margins to create new spaces, their own spaces, to resist and create hopeful and robust alternatives to unsustainable and unequal food regimes (Kloppenburg 2014; Ajates 2021).

The high energy demands of digitalising all aspects of society and nature must not be ignored either. Fulfilling promises of environmental sustainability based on the digital interconnection of all realms of life, including seed genetic material, would require more electricity than can be produced at the moment. Fossil fuels would not be an option. And as Dubay and Gras (in García 2021) have pointed out, a reliance on renewable sources would not realise this vision due to limitations of metals and grid stability. As the authors suggest, 'the world can be either green or digital, but not both' (García 2021). Until the time when a fair and fully renewable energy system is achieved, the fallacy of interconnection strengthens the argument for *in situ* PGRFA conservation. Blockchain technology has been proposed to track the use of DSI or any breaches of its licensing terms (Scholz et al. 2020). Again, blockchain might be helpful in the future, once the technology is less energy demanding – or renewable energy is abundant – and when a decentralised system, rather than one coordinated by the CBD and TPGRFA, would be more favourable to this decentralised technology. Under an OSS model, companies would still be able to develop new varieties but could not patent them. New models for financing breeding programmes would emerge. For example, publicly funded or cooperative-funded farmer-led sustainable blockchain systems and community data trusts – based on community land trusts – could be explored (Newton 2015). From a cultivated diversity perspective, territorialised varieties should be developed, as opposed to current patented varieties which are expected to adapt well to anywhere in the world just so they can be marketed to a bigger market. Furthermore, at the moment, new improved IPR-restricted varieties include in many cases biodiversity that was in the farmers' own country in the first place (Fraser 2019). The last few decades have shown how IPRs on PGRFA and plant genetic diversity are mutually exclusive.

The current system of governance for biodiversity and PGRFA embodies at its core an unhelpful compromise between disparate worldviews: on the one hand, some feel it continues to undermine biodiversity research and IPR, while others argue that it fails to challenge regimes of property around resources and thus cements the neoliberalisation of biodiversity (Nawaz, Satterfield, and Hagerman 2021). DSI is exacerbating these competing worldviews. Legal, financial and biology debates are occurring,, rendering technical (Li 2007) what is in fact, an ethical debate about whether life should be patented and privatised. We need collective solutions for DSI. DSI gives us the opportunity to scale up the OSS model. An OSS model would not weaken the current legal framework; it would strengthen it and its biodiversity objectives. For example, varieties whose protection period has expired should be declared 'open source'. And separate registration procedures with simplified criteria other than DUS (Distinctness, Uniformity, and Stability) and VCU (Value for Cultivation and Use) could be developed for traditional and participatory open source varieties (HIVOS & Biodiversity International 2018). Since the ethical and moral reasoning to protect biodiversity to sustain life on earth and social justice have not worked, law is becoming the latest arena for sustainability struggles to avoid further enchroachments on rights and abuses of the environment (see e.g. the developmentof ecocide law (Crook et al. 2018)). OS opens up another legal tool to protect seed. The main limitation to the OSS model is that it requires political will from states to adopt a long-term view to biodiversity and cultivated diversity conservation. OSSS encourages a change of mindset, an opportunity to reimagine terms of accessibility to PGRFA, from both a technological and a logistics perspective. For example, national, regional and community public gene banks could host DSI databases of local PGRFA in the future, improving logistic access. Regional innovative extension services would need to be extended to include participatory breeding, so that the benefits of DSI become materialised in the fields and the cycle between farmers and DSI is closed and mutually beneficial.

Conclusion

In this paper I locate the emergence of new digitalisation practices of PGRFA against the background of a broader set of processes that Goodman et al. (1987) referred to as industrial appropriation and substitutionism of natural and social aspects of food production. Industrial capital's increasing control of the natural processes and resources that are part of food production aims to reduce fluctuations and unpredictability and automate and standardise processes and yields to secure return on investment. These techniques have evolved with the technologies of each IR, and affect manufacturing, distribution and seed systems.

The current Fourth IR is characterised by a fusion of 'disruptive' technologies, whose interaction is blurring the lines between physical, digital and biological domains (Schwab 2016). These have introduced novel mechanisms of private enclosures of natural resources, with historical ones, such as land enclosures, still taking place. I have analysed how the growth of DSI and synthetic biology is contributing to the dematerialisation and fragmentation of PGRFA, creating new challenges but also opportunities for resisting privatisation and further loss of cultivated diversity. The paper has identified five types of enclosures facing PGRFA and the farmers who over centuries have developed and protected its biodiversity – logistic, financial, legal, social and technological enclosures– as well as the potential solutions an OSS model could contribute in order to achieve fairer and more sustainable seed systems.

The analysis of these series of interrelated enclosures shows that the grab of PGRFA is not new to the food system, and not new to seed. The industrialisation, globalisation, privatisation and market concentration that have characterised other aspects of the food system have also reached the realm of seeds. Similarly to humans, seeds are also being severed from natural environments, suffering the increased concentration of capital and control over resources (natural and human). Twenty-first-century biotechnology has evolved closely interwoven with the rise of digital agriculture, AI, robotics, and other elements of so-called 'AgTech' (Dauvergne 2020; Montenegro de Wit 2021). These developments have been facilitated and accelerated by intellectual property regimes and trade liberalisation trends that, in the case of seed, have functioned mostly to legitimate and institutionalise their continued appropriation (Kloppenbourg 2014).

DSI highlights the fact that biodiversity and our associated knowledge of it is and should remain boundless. The challenges identified to incorporate the Parts Agenda into the current ABS system accentuate how imposing a reductionist model on the smallest components of life is emerging as the frontier-IPR based agribusiness model. A model that allows no more IPR restrictions on living organisms or any of their parts would provide a systemic solution to technological, administrative, conservation, social justice and open-science problems.

The rise of DSI offers a critical juncture to the seed sovereignty movement. The collapse, for the first time in its history, of the ITPGRFA negotiations to agree new ABS terms for DSI has, on one hand, extended the legal vacuum period during which companies are able to continue to grow their big data sets of DSI. On the other hand, the DSI impasse could well be seized as an opportunity to categorise it as digital commons and, with it, help to democratise food systems, distribute power and protect cultivated diversity. Connecting to the digital commons community complements and enlarges efforts and work on food systems change, connecting it to wider forces and issues beyond food and agriculture. OSS encourages us to think more about vertical and horizontal linkages and processes, including the diverse and evolving drivers and barriers that shape possibilities for food systems change, navigating between physical and digital struggles. Seed struggles indicate how food sovereignty is fast becoming a digital affair inextricable and indissoluble from data sovereignty (Fraser 2019) and technology sovereignty (Montenegro de Wit 2021).

Future research pathways for developing the OSS approach to DSI include organic heterogeneous material, OSS business and livelihood models, and the investigation of how a form of community data trusts could work for OSS, as well as new models for applying collective copyleft licences to heirloom varieties and other varieties developed by communities for which finding a single individual developer/breeder would be complicated. Furthermore, concerns from farming communities about licence regimes, even if open source, are valid and need to be acknowledged and further explored. Seeds were once owned by nobody. However, their digitalisation and dematerialisation mean that seeds not owned by anybody are more susceptible to appropriation. OSS can enable the ownership of seeds by everybody rather than by nobody.

A confluence of intensifying political, climatic and digital circumstances accelerated by the Fourth IR has created a new urgency and challenges for food systems that beckon us to 'think more broadly and engage more boldly' (Hinrichs 2014:144). The utility of the open-source concept and movement, their potential to open up new angles, and the growing complexity of the pressing challenges facing seed systems, all build the case for exploring the OSS concept and supporting the OSS movement, going beyond its current application on physical seedto offering a fair and democratic solution to DSI governance. Recognising farmers' role and knowledge in developing and protecting biodiversity, and their access to it, is essential (Nishikawa and Pimbert 2022). Both ontological and normative ideas of progress around seed and biodiversity management and seed sovereignty are thus best represented not as a single-track reductionist and technical race but as endeavours to be reached by a variety of paths and mechanisms that ensure cultivated biodiversity and farmers' right to seed across *in situ*, *ex situ*, *in silico* and *trans situ* contexts and across physical and digital realms. For it to work, an OSS model should adopt an integrated approach to conservation, research and education, working from local to global scales to overcome the digital and socio-economic divide. The adoption of an OSS model for DSI requires political will from states willing to adopt a long-term view of biodiversity and cultivated diversity conservation. The OSS model answer might seem for many stakeholders a far-fetched option at the moment; however, the climate emergency and unrelenting loss of diversity require bold action, and the implausible possibilities of today will soon become politically and existentially unavoidable.

Acknowledgements

I am grateful to the anonymous reviewers for their careful reading of the article and their constructive and insightful comments and suggestions.

Funding

This work was supported by Fundación Daniel y Nina Carasso: [Grant Number 2021 Daniel Carasso Fellowship].

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Raquel Ajates is a Research Fellow at Universidad Nacional de Educación a Distancia (Spain), working on open source seeds and food policy. Previously, Dr. Ajates was a Post Doctoral Researcher University of Dundee, and a Teaching Fellow in the Interdisciplinary Food Systems Teaching and Learning programme at the Centre for Food Policy at City University of London, where she completed her PhD and MSc in Food Policy. Her research interests include pathways to regenerative food systems, seed governance, cooperatives, alternative food networks, agroecology, food policy and citizen science.

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