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Evaluating the 2014 Nagoya Protocol
Effects on International Exchanges of Plant Genetic Resources

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Abstract

The international rules governing the conservation, exchange, and use of plant genetic resources for food and agriculture (PGRFA) have evolved through agreements including the 1993 Convention on Biological Diversity, the 2004 International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), and the 2014 Nagoya Protocol (NP), which seeks fair and equitable benefit sharing from the use of PGRFA. Yet limited evidence on how these rules affect the international movement of PGRFA used by genebanks and breeding programs remains. This study assesses the NP's effects using cross-country panel data from the GENESYS database. Leveraging countries' staggered entry into the NP, we apply the difference-in-differences method developed by Callaway and Sant'Anna (2021) and gravity-model analyses that account for NP membership and general regulatory capacity in provider and recipient countries. Results indicate that joining the NP has often reduced the number of PGRFA accessions exchanged internationally, particularly for pearl millet and wheat, with negative effects persisting in multiple years after 2014. Adverse effects are also observed for other crops during substantial portions of the study period. These effects are more pronounced for countries with limited regulatory capacity to formulate and implement sound policies and regulations, proxied by the World Bank's regulatory quality index. The findings are consistent with the hypothesis and emerging anecdotal evidence that complex access and benefit-sharing requirements discourage PGRFA exchanges because of legal uncertainty, administrative costs, and limited institutional capacity, although more formal empirical analysis is needed to test the hypothesis. Policy priorities include reviewing and streamlining NP implementation and its coordination with other exchange frameworks for certain subgroups of PGRFA, such as the ITPGRFA, that are supposed to operate separately from the NP, especially where procedures are unclear or duplicative, while investing in the legal, administrative, and genebank capacity needed to facilitate compliant PGRFA exchanges. These measures can help protect equitable benefit sharing without unnecessarily restricting access to crop diversity needed for food security, crop improvement, and climate adaptation.

Keywords: Genetic resources policy, genebanks, germplasm, crop improvement, plant genetic resources for food and agriculture, Nagoya Protocol, Callaway-Sant'Anna Difference-in-Differences method, cross-country panel data

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Acronyms

ABS	Access and Benefit Sharing
AgIPR	Agricultural Intellectual Property Rights
ASTI	Agricultural Science and Technology Indicators
CBD	Convention on Biological Diversity
CRE	Correlated Random Effects
CSDID	Callaway-Sant’Anna Difference-in-Differences
DID	Difference-in-Differences
EURISCO	European Search Catalogue for Plant Genetic Resources
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GENESYS	Global Portal on Plant Genetic Resources
IPR	Intellectual Property Rights
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
LMICs	Low- and Middle-Income Countries
NBS	National Biodiversity Score
NP	Nagoya Protocol
NPGS	National Plant Germplasm System
PGRFA	Plant Genetic Resources for Food and Agriculture
RC	Regulatory Capacity
ROW	Rest of the World
SMTA	Standard Material Transfer Agreement
UPOV	International Union for the Protection of New Varieties of Plants
USDA	United States Department of Agriculture
WGI	Worldwide Governance Indicators (if used)

1 Background

Improved crop varieties play a critical role in enhancing agricultural productivity worldwide, particularly in the Global South, where poverty and food insecurity pose significant development challenges (Evenson & Gollin 2003; Walker & Alwang 2015; Lynam et al. 2016). Crop improvement programs have contributed not only to higher yields and output for smallholder farmers, but also to their capacity to withstand shocks (FAO et al. 2018), improve nutritional security, conserve biodiversity, and address concerns over the environmental sustainability of agricultural production (Davis et al. 2019; Baldos et al. 2020). The international conservation and exchange of germplasm used to develop these improved varieties is a major contributor to these outcomes. Subsequent international treaties and conventions were later agreed upon by countries to ensure the fair and equitable sharing of benefits arising from the utilization of genetic resources (Evenson & Gollin 2003; Walker & Alwang 2015; Lynam et al. 2016; Smith et al., 2021).

The global governance system that shapes the conservation, exchange, and use of plant genetic resources for food and agriculture (PGRFA) has evolved considerably during the last few decades. Notable agreements include the 1991 revision to the International Convention for the Protection of New Varieties of Plants, the 1993 Convention on Biological Diversity (CBD), the 2004 International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), and the 2014 Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity (NP). Taken together, these agreements form a patchwork of rules, norms, and guidelines that influence how countries manage their PGRFA endowments, how they pursue intellectual property rights over PGRFA, and how they reward farmers and innovators who conserve, improve, and share PGRFA, among many other functions. However, not all countries subscribe to every agreement, and some subscribe to none at all; yet the agreements still exert considerable influence on how genebank collections, crop improvement programs, and seed markets operate around the world. In short, international agreements governing PGRFA often have competing agendas around promoting biodiversity conservation and incentivizing free exchange.

Questions of access through free exchange also have crucial benefit-sharing implications. For example, there are persistent concerns about whether elements of these agreements hinder the free and unfettered exchange of PGRFA that benefit low- and middle-income countries where agricultural productivity, food security, and climate adaptation remain high on many national

development agendas. For example, early studies by Javier & Toledo (2013) and Alston & Pardey (2014) showed that the CBD—an agreement that spotlighted a country’s sovereignty over its PGRFA endowments and the benefits associated with their exchange and use—had a dampening effect on the cross-country flow of PGRFA since the mid-1990s. Recent evidence from Mekonnen & Spielman (2021) echo these findings by demonstrating the association between a country becoming party to the CBD and a reduction in the international exchange of PGRFA.

In fact, these effects might be more significant than the effects of stronger intellectual property rights (IPRs) introduced into national laws in a manner consistent with the International Union for the Protection of New Varieties of Plants (UPOV), which administers the International Convention for the Protection of New Varieties of Plants. The influence of IPRs over PGRFA exchanges is ambiguous (as discussed briefly in later sections), with findings from prior studies suggesting positive, negative, and null effects (see for example, Binenbaum et al. 2003; Thomson 2015; Spielman & Ma 2016; Zhou et al. 2018).

In partial response to these issues, the international community put forth the ITPGRFA as a mechanism to reiterate and codify the global commitment to PGRFA conservation, exchange, and use. A decade later, the NP came into effect as a supplementary agreement to the CBD to establish a legal framework for the implementation of fair and equitable benefit-sharing arising from the use of a country’s genetic resource endowment. While the NP’s aim is to bolster access and benefit-sharing (ABS), it also introduces certain costs—both direct and indirect, as well as monetary and nonmonetary—on the global exchange and use of PGRFA.

Despite these concerns, there are few studies that examine and quantify the NP’s impact, leaving critical knowledge gaps regarding its effects on the global governance system. This study addresses these knowledge gaps by using data from GENESYS (2024), which is a repository of cross-country transfers from more than 4.3 million PGRFA accessions (as of September 2024) held in over 500 institutes worldwide. To assess the impact of countries becoming party to the NP, we apply two novel empirical approaches. First, we use the recently developed modified difference-in-differences (CSDID hereafter) method by Callaway & Sant’Anna (2021) to assess the impact of a country becoming party to the NP. Second, we apply gravity models commonly used in international trade studies (Grant & Boys 2012), as well as generalized double-hurdle models (Yen 1993; Takeshima & Liu 2020), to examine how the regulatory capacity of provider and recipient countries influences PGRFA exchanges.

This study contributes to several strands of literature. First, it contributes to the literature on international PGRFA exchange (Evenson & Gollin 1997, 2003) and related issues of technology transfers (Zhou et al. 2018) by providing empirical evidence on how these exchanges and trade can be affected by global policy regimes. Relatedly, the study contributes to the literature on the roles of regulatory capacity and its effect on how countries benefit from elements in the global policy regime governing PGRFA exchange and use (Kent 2004; Yang & Woo 2006; Kolady & Lesser 2009; Joshi et al. 2014; Thomson 2015; Tsang et al. 2016; Qaim 2020; Campi & Nuvolari 2021; Kuhlmann et al. 2025). Specifically, we provide cross-country evidence suggesting that intensified regulations can suppress PGRFA exchanges due to either provider countries or recipient countries being party to the NP. Lastly, this study expands the methodological toolbox used in applied economics to study the effects of policy changes by using the CSDID approach (Sant’Anna and Zhao 2020; Callaway & Sant’Anna 2021), gravity models (Grant & Boys 2012), and the generalized double-hurdle model (Ricker-Gilbert et al. 2011; Takeshima & Nkonya 2014; Takeshima & Liu 2020) to study global PGRFA exchanges.

The remainder of the paper is structured as follows. Section 2 provides a brief overview of the evolution of global PGRFA exchange regimes, including the NP. Section 3 provides an overview of our data and data sources. Section 4 presents the empirical methods employed in the analysis. Section 5 presents and discusses the results, followed by policy recommendations and concluding remarks in Section 6.

2 Global PGRFA exchanges and the Nagoya Protocol

Beginning in the 1950s, international exchange of PGRFA increased significantly as public investment in crop improvement programs came to play a significant role in national strategies for agricultural development and economic growth in many low- and middle-income countries (LMICs) (Marden et al. 2023; Halewood et al. 2020). Advances in plant breeding went hand in glove with a growing global interest in accessing and conserving genetic resources (Curry, 2017). With this growing interest came geopolitical concerns of sovereignty over crops’ centers of origin and a need to establish a multilateral genetic resource governance system to regulate exchange (Bonneuil, 2019). Generally speaking, the key elements of the evolution of global regimes governing PGRFA exchange during the modern era have revolved around optimizing tradeoffs among key contrasting objectives, that is, enhancing cross-country PGRFA exchanges (treating PGRFA as global public goods) and maximizing attribution of benefits from such exchanges to

countries providing PGRFA (protecting benefits for the private entities providing these PGRFA). Over time, PGRFA have been exchanged globally through various modalities, including new acquisition by global genebanks, deposits of existing collections, transfer between countries, new collection missions, global breeding programs, and other collaborative scientific efforts (Mekonnen & Spielman 2021). During the 1960s through the late 1980s, exchanges through these modalities were relatively less regulated and further facilitated by the establishment of global institutions including the Consultative Group on International Agricultural Research (CGIAR)¹ (Fowler et al. 2001; Fuglie & Echeverria 2024). The International Undertaking on Plant Genetic Resources in 1983 explicitly states that PGRFA were the “common heritage of mankind (*sic*)” (Moore & Tymowski, 2005).

At the same time, there was a growing recognition of the cultural, economic, and ecological value of PGRFA, particularly in the LMICs where the largest share of the world’s biodiversity resides. In other words, biodiversity conservation and global equity were increasingly pushed into international treaty negotiations. These concerns led to the CBD, signed in December 1993, partly to establish national sovereignty over PGRFA and other forms of biological diversity. The CBD includes provisions that aim to ensure equitable access to and sharing of benefits derived from biological diversity, covering broad classes of materials including plant, animal, microbial, and other origin materials containing functional units of heredity (Pauchard 2017; Mekonnen & Spielman 2021). A consequence of the CBD was a reduction in the extent and speed of global PGRFA exchanges (Jinnah & Jungcurt 2009; Welch et al. 2013, 2017).

The first significant global effort to reverse the CBD’s protectionist principles came in the form of the 2004 ITPGRFA and the FAO’s in-trust agreements with CGIAR’s genebanks (Mekonnen & Spielman 2021; Marden et al. 2023). An essential feature of the ITPGRFA was its provisions meant to facilitate the cross-country exchange of PGRFA for crops deemed to be of extreme importance to global food security (a total of 35 food staple crops and 29 forage crops listed in Annex 1 of the Treaty), and the required use of Standard Material Transfer Agreements

¹The CGIAR was constituted in 1971 by a group of donors to coordinate support for an emerging collection of PGRFA for staple crops by international agricultural research centers, the first of which was established in 1960 (Fuglie & Echeverria 2024).

(SMTAs) that obviate the need for provider and recipient countries to negotiate new terms and conditions for PGRFA transfers (Marden et al. 2023).

Evidence indicates that the ITPGRFA has contributed to, or is at least closely correlated with, increases in PGRFA exchanges between countries (Gotor & Caracciolo 2010; Halewood et al. 2012, 2020; Galluzzi et al. 2016). Yet in the decade that followed, relatively little progress was made on the implementation of mechanisms for ABS, despite ABS being a shared principle of both the CBD and ITPGRFA.

In 2014, the NP was meant to address this gap in the global governance landscape for ABS. The NP provided guidance for the design of legal and institutional frameworks for ABS, such as requirements for national policy and legislation; regulatory and procedural mechanisms; national authorities for the management of biological diversity exchanges; and monitoring systems to provide all parties with transparency on the exchange, access, and sharing of benefits (Marden et al. 2023). NP provisions also extend beyond the CBD's original intent for the protocol, for example, by ensuring that benefits are shared with indigenous and local communities that hold the genetic resources or traditional knowledge and the establishment of prior informed consent and mutually agreed terms with these communities (in addition to relevant national authorities as originally required under CBD) (Marden et al. 2023).

While the NP's framework for ABS seems to introduce new and more stringent restrictions on the movement of PGRFA, it also has limits. Specifically, the NP does not hinder ITPGRFA member countries from exchanging PGRFA for Annex 1 crops under SMTAs for the purpose of research, breeding, and training related to food and agriculture (Marden et al. 2023). However, there may be indirect and unintended effects of the NP on PGRFA exchanges by both provider and recipient countries. First, the NP still applies if either provider or recipient countries are *not* members of ITPGRFA. Second, regulations under the NP also apply to food security-related PGRFA identified under the ITPGRFA—that is, the aforementioned 35 food crops and 29 forage crops—under certain conditions, such as the development of pharmaceuticals, biofuels, or other industrial uses, all of which are considered to be beyond the ITPGRFA's mandate (Marden et al. 2023, Figure 2). This suggests that, even if the initial purpose of a PGRFA transfer is consistent with the ITPGRFA's mandate, a provider country can flag concerns about indirect or secondary uses that, in turn, could discourage the exchange in question or any subsequent exchanges (Marden et al. 2023). Relatedly, there are practical questions and concerns about a country's capacity to

determine when the NP or ITPGRFA applies to a PGRFA exchange given the complexity of these agreements (Girard & Frison 2018; Halewood et al. 2018; Marden et al. 2023). It may be the case that the institutional investments required to manage transfers in compliance with the NP and ITPGRFA, including the national policies, laws, regulations, procedures, and competent authorities to implement these policies, laws, regulations, and procedures, will themselves draw resources away from the actual use of PGRFA for breeding, as often suggested by anecdotal evidence based on practitioners' experiences in the NP member countries (see for example, Cabrera Medaglia 2022; Colella et al. 2023; Ivey et al. 2023).

Lastly, the NP can still have significant effects on ITPGRFA countries because the ITPGRFA's implementation is often imperfect. Although they were designed to operate complementarily, the parallel systems present legal and institutional complexity. For example, recipient countries may lack the regulatory capacity to fully compensate certain PGRFA beneficiaries, like farmers or indigenous communities, in donating countries pursuant to the ITPGRFA. As a result, this can incentivize donating countries to pursue stronger legal frameworks afforded under the NP instead of donating PGRFA through the ITPGRFA (see Prip 2024). Similarly, provider countries may consider the benefit-sharing mechanisms in the ITPGRFA's Multilateral System to be ambiguous or the SMTA too complex (Mulesa & Westengen 2020), further incentivizing these countries to pursue the PGRFA exchange through the NP. Because the ITPGRFA was not negotiated in concert with the CBD, some countries can be skeptical of the ITPGRFA's legal status (Moody 2016), which could potentially influence their willingness to exchange PGRFA through the ITPGRFA's Multilateral System. This paper contributes to further understanding whether and how these parallel governance arrangements affect the exchange of PGRFA between countries.

3 Data sources and descriptive statistics

Our primary data on cross-country PGRFA transfers come from GENESYS, which is a global portal that was jointly developed by Bioversity International, the Global Crop Diversity Trust, and the Secretariat of the ITPGRFA.² GENESYS is estimated to cover approximately half of all accessions held worldwide. As of mid-2024, GENESYS contained data on more than 4.3 million accessions held in over 500 institutes worldwide, including CGIAR genebanks, the U.S.

²<https://www.genesys-pgr.org/content/about>.

Department of Agriculture’s National Plant Germplasm System (NPGS), and EURISCO, a web-based catalog that provides information about *ex-situ* plant collections maintained in Europe (GENESYS 2024).³

We focus on seven major crops: beans (common beans, *Phaseolus vulgaris*), cowpea, maize, pearl millet, rice, sorghum, and wheat. As of March 2024, GENESYS recorded over 1.1 million accessions of these crops worldwide. These crops and their derived products are key to food security, accounting for 43 percent of total caloric intakes globally and 51 percent in the least developed countries in 2021 (FAO 2024).

We complement the GENESYS data with select other sources to construct the relevant control variables described in the previous section. Data on ABS regulations and the national biodiversity score (NBS) are from Mekonnen & Spielman (2021). GDP per capita (in 2015 USD) data, trade openness data, and the regulatory quality index are from the World Bank (2024a, 2024b). Harvested areas under each crop are taken from the FAO (2024). Annual agricultural R&D spending figures are from ASTI (2024), with additional data from Nin-Pratt (2021) for developing countries and Heisey & Fuglie (2018) for high-income countries. The agricultural intellectual property rights (IPR) index is drawn from Campi & Nuvolari (2021).

Table 1 summarizes the average number of genebank accessions per year provided to genebanks in the CGIAR, the U.S., and the rest of the world (ROW), computed for each policy regime period, that is, the pre-CBD, CBD, ITPGRFA, and NP decades, using data from GENESYS. Similarly, Table 2 summarizes the network size (total number of countries donating accessions to each genebank group in any year within each decade). These tables extend the analysis of Mekonnen & Spielman (2021, Tables 1 and 2) by adding records from the NP era (2014–2022) and updating previous data with newly available GENESYS data.

The figures in these tables indicate that the number of genebank accessions and network sizes fluctuate across genebanks and crops. During the NP era, the number of accessions received by ROW genebanks generally increased, whereas accessions by CGIAR genebanks generally

³Importantly, the GENESYS data simply capture newly registered accessions in recipient countries and provider countries for each of these accessions but typically do not record the nature of these exchanges. For example, the GENESYS data do not distinguish an accession received in a standalone manner from a group of accessions received as part of the same breeding programs. Furthermore, if the accession is provided from the recipient country to a third country (different from the original provider country), then the recipient country is recorded as the providing country for the accessions recorded in that third country. Our empirical framework models these mechanisms implicitly rather than explicitly, focusing on the count of accessions exchanged between countries in a given year.

decreased (except sorghum), and accessions by U.S. genebanks nearly ceased. In terms of network structures, donations to CGIAR seem to have become more decentralized, with an increasing number of provider countries relative to total accessions. In contrast, networks have become more concentrated for ROW.⁴

Table 3 presents summary statistics for the control variables. Given the global nature of our data, we show statistics differentiated by the World Bank-classified income groups to which each country belonged in a given year. The data reveal that several variables—such as trade openness, regulatory quality, agricultural R&D spending, agricultural IPR index, and the presence of ABS regulations—are generally positively correlated with income levels. Nonetheless, due to significant fluctuations within and between countries over time in each income group, correlation coefficients among these variables are relatively low (with average correlation coefficients of 0.1), minimizing concerns about multicollinearity problems in the analysis. Additionally, the historical averages of the number of accession donations made between 1961 and 1980, which we included to control for countries' inherent tendencies to donate accessions, do not show noticeable correlations with income levels.

Table 4 summarizes the evolution of the number of countries becoming party to the NP. In 2014, the first year that the NP came into effect, about 50 countries became party, accounting for only about 25 percent of all countries. Between 2015 and 2022, an additional 84 countries joined. This variation in timing across countries reinforces the relevance of applying the CSDID method.

Figure 2 presents the regional distribution of provider and recipient countries in PGRFA exchanges recorded in GENESYS for wheat (similar figures for other crops are provided in Appendix **Error! Reference source not found.**). The compositions of major regions vary considerably across crops, partly suggesting that our analyses are applicable to broad contexts. More specifically, a majority of maize and wheat PGRFA exchanges have been among relatively more developed regions (Oceania, Europe, and Central/South America). On the other hand, a significant majority of cowpea, millet, rice, and sorghum germplasm exchanges have been among relatively less developed regions (South or Southeast Asia and Africa), while most bean exchanges

⁴In theory, the patterns of accession flows can be highly irregular (spasmodic) and sequential (dynamically affected by the previous flows of accessions). Nonetheless, accession flows can also be highly affected by idiosyncratic factors in the providing countries in a given year, rather than demand from the recipient countries. This is primarily due to the noncommercial nature of accession provisions for staple crops, whose supply is still significantly determined by public-sector research organizations and/or breeders. These idiosyncratic shocks are largely exogenous to the flow of accessions from the perspective of recipient countries'.

have been within the Americas (with some increase in Eastern Africa since 2014). The active participation of LMICs, particularly for the latter set of crops, underscores the importance of understanding the NP’s impact on germplasm exchanges for global food security. These patterns suggest that the returns to accessing new PGRFA from abroad may be higher in LMICs, where the in-country stock of PGRFA is relatively limited, compared to higher-income countries that have accumulated diverse PGRFA collections over time through historical inflows of foreign PGRFA or domestic plant breeding efforts.

4 Empirical approach

As noted earlier, our analysis focuses on two dimensions of the research question: (a) what are the average effects of a country becoming party to the NP on PGRFA sharing; and (b) how does the NP status of recipient countries, along with the regulatory capacity of both provider and recipient countries, introduce heterogeneity to these effects? In the first analysis, we apply the CSDID method to estimate average effects. In the second analysis, where CSDID is less suitable, we use a more general gravity-model framework with a generalized double-hurdle model. Importantly, our aim is not to pit one model against the other but rather to show the robustness of our findings by drawing insights from both approaches.

4.1 The Callaway & Sant’Anna (2021) difference-in-differences (CSDID) method

Under reasonable assumptions, the CSDID method can provide more rigorous insights into causal effects than more conventional two-way fixed effects models. The model is particularly suitable for our empirical setting, which is characterized by (i) multiple time periods in both pre-and post-treatment periods, (ii) variation in treatment timing, and (iii) the potential for the “parallel trends assumption” to hold only after conditioning on observed covariates.⁵ The CSDID method explicitly identifies group–time average treatment effects across different groups and time periods, allowing for the detection of treatment effect heterogeneity (Callaway & Sant’Anna 2021). This allows for consideration of three different types of average treatment effects: (i) *calendar-time effects*, (ii) *event-study type effects* or *dynamic effects*, and (iii) *group/cohort effects*. Each is discussed later in this section as it relates to our empirical approach.

The basic setup of the CSDID method is as follows (Callaway & Sant’Anna 2021):

⁵In the results section, we show that the assumption of parallel trends is in fact valid in our sample.

$$Y_{it} = Y_{it}(0) + \sum_{g=2014}^{\mathcal{T}=2022} (Y_{it}(g) - Y_{it}(0)) \cdot G_{i,g}. \quad (1)$$

The term Y_{it} is the observed number of accessions donated by the country i in year t .⁶ Notation g refers to the year a country becomes a signatory of the NP ($g = 2014, 2015, \dots$). Hereafter, all countries signed the NP in year g are grouped into “group g .” $Y_{it}(0)$ denotes country i ’s potential outcome when it remains untreated (that is, not being party to the NP) through time period $\mathcal{T} = 2022$. $Y_{it}(g \neq 0)$ denotes the potential outcome of Y_{it} that country i would experience at year t if it were to first become party to the NP in year g . $G_{i,g} = 1$ if country i belongs to group of countries that first signed the NP in year g , and 0 otherwise ($G_{i,g}$ is time-invariant across t). However, we only observe one potential outcome path for each country. Observed outcomes for countries that did not become NP signatories in any year throughout 2022 are considered untreated potential outcomes in all periods (Callaway & Sant’Anna, 2021). Conversely, observed outcomes of countries that became NP signatories before or in 2022, are considered country-specific potential outcomes corresponding to the particular group of countries that first become NP signatories in period g .

We first obtain

$$ATT(g, t) = \mathbb{E}[Y_t(g) - Y_t(0) | G_g = 1]. \quad (2)$$

which is the average treatment effect at year t for countries belonging to group g . $ATT(g, t)$ is estimated for each group g and for each year t , through Sant’Anna and Zhao’s (2020) doubly robust DID estimator based on variants of inverse probability weighting (IPW). Applying the IPW approach removes the potential bias in $ATT(g, t)$, which would otherwise remain given that self-selection into the NP of country i can be an endogenous response to exogenous conditions

⁶While we primarily use the natural log transformation (positive) of the total number of accessions donated by country i in year t , as discussed in section **Error! Reference source not found.**, we use nontransformed variables of Y_{it} in CSDID method. This is because, raw Y_{it} skews significant to the right, but this skewness is largely driven by the skewness in unobserved country-fixed effects. Thus, once conditioned on country-fixed effects, Y_{it} in the DID equation (1) is much less skewed (with skewness index dropping to about 1/10 of skewness in raw data).

(proxied by $X_{i\hat{t}}$) in year $\hat{t}$. By accounting for this selection bias, the reweighted estimates provide a more accurate measure of the causal effect of NP membership.⁷

Specifically, following standard IPW approaches, $ATT(g, t)$ is estimated by reweighting the sample using $1/p_i(X_{i\hat{t}})$ where p_i is the probability that country i becomes an NP member given its exogenous characteristics in year $\hat{t}$, the year it actually joined the NP. X_0 consists of variables that can explain the trend of germplasm transfers beyond becoming parties to NP. Following Mekonnen & Spielman (2021), $X_{i\hat{t}}$ includes per capita GDP, whether the country i had access and benefit sharing (ABS) regulations in place, agricultural R&D spending (measured in constant USD) (ASTI 2024; Heisey & Fuglie 2018, Nin-Pratt 2021), regulatory quality index (World Bank 2024b), agricultural IPR index for plant variety protection (Campi & Nuvolari 2021), and trade openness (World Bank 2024a) in year $\hat{t}$. Regulatory capacity and trade openness have often been closely associated with technology transfers and use of IPRs (see Kolady & Lesser 2009; Joshi et al. 2014; Tsang et al. 2016; Campi & Nuvolari), although the effects of IPRs on the outcomes of crop improvement investments may be ambiguous, as noted earlier. Additionally, $X_{i\hat{t}}$ includes other time-invariant factors, such as NBS (Mekonnen & Spielman 2021), as well as the average number of PGRFA transferred per year during the period between 1961 and 1983, which is the period preceding the primary focus of this analysis.

The estimated $ATT(g, t)$ values serve as fundamental building blocks that are subsequently aggregated to obtain more relevant estimands, as shown in the following sections.

4.1.1 Estimations of aggregated causal effects

The estimated $ATT(g, t)$ values can be disaggregated in three different ways: (i) calendar-time effects, (ii) event-study type effects or dynamic effects, and (iii) group/cohort effects. The calendar-time effects are the average effect in year t of becoming an NP member across all countries that had become NP signatories by year t , or

$$\theta_c(t) = \sum_{g \in \mathcal{G}} \mathbf{1}\{t \geq g\} P(G = g | G \leq t) ATT(g, t). \quad (3)$$

⁷As highlighted also in Sant'Anna and Zhao (2020), the IPW approach originally proposed by Moffitt et al. (1999) has long been used in the impact evaluation literature in observational settings (see for example, Imbens & Wooldridge 2009). Conceptually, IPW transforms NP member countries and nonmember countries into comparable samples using the inverse of propensity for treatment based on observable characteristics of countries, so that, under the assumption of selection-on-observables, remaining differences in outcomes (provision of PGRFA to other countries) can be more closely attributed to being a NP member.

Equation (3) can be interpreted as how countries that had become an NP party by year t , on average, experienced changes in the number of accessions they donate in year t , compared to the counterfactual scenario in which they had not joined the NP until after year t .

The event-study type effects, or dynamic effects, are the average effects of being an NP party for e years, capturing how the ATT evolves over time.⁸ This is estimated across all groups ever observed to have participated in the treatment for exactly e years.

$$\theta_{es}(e) = \sum_{g \in \mathcal{G}} \mathbf{1}\{g + e \leq T\} P(G = g | G + e \leq T) ATT(g, g + e). \quad (4)$$

The group/cohort effects capture the average effects for countries that joined the NP in particular year g (group g), separately for each group. Figure 1 illustrates the relationship between $ATT(g, t)$ and each of the aggregated estimators.

The three types of effects capture different dimensions of the average impact. Calendar-time effects show how countries that had already joined the NP behaved in a given year compared with how they would have behaved without joining, averaging across all countries that were NP members in that year. Dynamic effects describe how the impact of joining evolves with the number of years since accession, averaging across countries that have spent the same amount of time in the NP. Cohort effects compare countries based on the year they joined, summarizing how each joining group experienced the NP and combining these patterns into an overall average effect across all countries that became NP members by 2022.

The overall effect of the NP is then constructed by a weighted average of the group/cohort-specific effects described above, where weights are proportional to the size, that is, the number, of each cohort, which returns the average effect of becoming an NP party, experienced by all countries that ever became NP signatories by 2022. All estimates are obtained using the STATA command `csdid` (Rios-Avila et al. 2021).

⁸We use this estimator simply to assess any indications of persistence, or fluctuations in the effects over time at country-levels, rather than rigorous investigations of exact comparisons across times (which require limiting the samples to countries that became NP signatories at the same year g , i.e., using 'parallel' option in CSDID event command.)

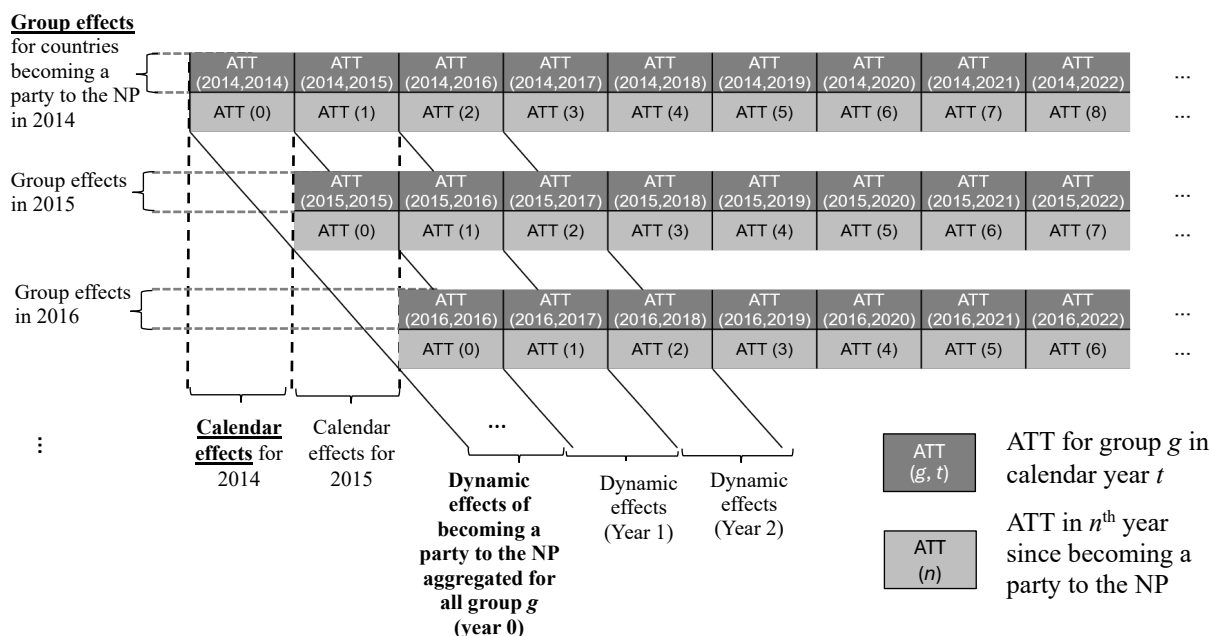


Figure 1. Illustration of estimators from CSDID method

Source: Authors.

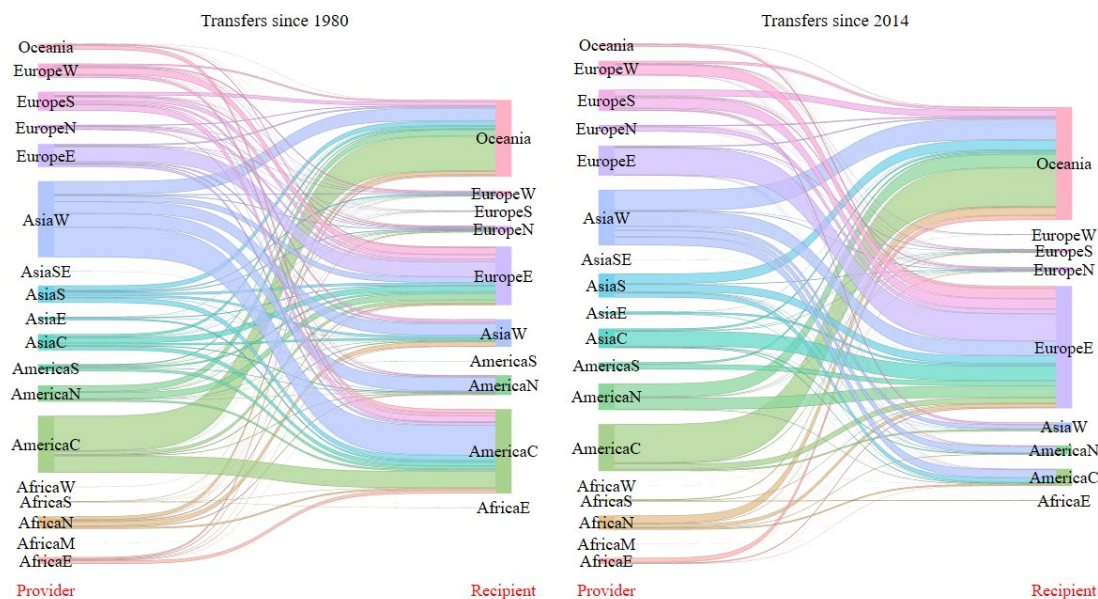


Figure 2. Sankey diagrams illustrating PGReFA provider and recipient countries, by region and periods (1980~2023 and 2014~2023), example of wheat

Source: Author's compilations.

4.2 Heterogeneity due to regulatory capacity and recipient countries' NP status

We now extend our analysis to examine the effects of being party to the NP to recipient countries and the roles of regulatory capacity in both provider and recipient countries. While these additional aspects are important, incorporating them into the CSDID method poses certain methodological challenges. Instead, we use gravity model approaches commonly used in modeling international trade of agricultural commodities (see, for example, Grant & Boys 2012) to reliably capture the heterogeneity and its correlates.⁹

Furthermore, we extend the gravity model to Cragg's (1971) double-hurdle framework, which is suitable for cases like ours in which there are many country-pair-year observations with zero PGRFA exchanges, resulting in truncated data. However, since a standard double-hurdle model can be sensitive to the distribution of nontruncated samples, we estimate a generalized double-hurdle model (Yen 1993), which has been applied in recent studies like Takeshima et al. 2017, to improve the robustness and reliability of the analysis. The model is presented as follows.

$$D_{ijt} = \text{Probit}(\alpha + \beta_{NI}NP_{it} + \beta_{NJ}NP_{jt} + \beta_{XI}X_{it} + \beta_{ZI}Z_i + \beta_{XJ}X_{jt} + \beta_{ZJ}Z_j + \beta_{\delta}\delta_{ij} + \beta_T T_{CBD,t} + \beta_T T_{ITPGRFA,t} + \beta_T T_{NP,t} + \beta_T T_{2020s,t} + \varepsilon_{ijt}) \quad (5)$$

(for each crop)

and

$$Y_{ijt}^* = \frac{Y_{ijt}^\lambda - 1}{\lambda} = \text{Truncated Regression}(\alpha + \beta_{NI}NP_{it} + \beta_{NJ}NP_{jt} + \beta_{XI}X_{it} + \beta_{ZI}Z_i + \beta_{XJ}X_{jt} + \beta_{ZJ}Z_j + \beta_{\delta}\delta_{ij} + \beta_T T_{CBD,t} + \beta_T T_{ITPGRFA,t} + \beta_T T_{NP,t} + \beta_T T_{2020s,t} + \varepsilon_{ijt}) \quad (6)$$

if $Y_{ijt} > 0$
(for each crop).

Variable NP_{it} is a binary variable indicating whether the donating country i was a party to the NP in year t , while NP_{jt} is a binary variable indicating whether the recipient country j of PGRFA from donating country i was a party to the NP in year t . X_{it} and Z_i are time-variant and time-invariant characteristics of donating country i in year t , while X_{jt} and Z_j are time-variant and time-invariant characteristics of the recipient country j . δ_{ij} is a variable that measures the physical distance

⁹ Our approach in this subsection is designed to answer multiple research questions while balancing statistical rigor across those questions equally. Our approach is not particularly designed to focus on a single question as CSDID does in the previous subsection (in which the question is the effect of being party to the NP of providing countries). A similar trade-off is also discussed in the literature comparing more general estimation frameworks that focus equally on multiple variables with the treatment effects literature that focuses more disproportionately on the treatment variable (e.g., Heckman & Vytlačil 2007).

between donating country i and recipient country j , obtained from Mayer & Zignago (2011) and previously used in Grant & Boys (2012). $T_{CBD,t}$, $T_{ITPGRFA,t}$, and $T_{NP,t}$ each indicate if the year t is in the CBD era (1993 onward), ITPGRFA era (2004 onward), and NP era (2014 onward). All other notations are as defined in earlier sections.

The Box-Cox transformation of Y_{it} in equation (6) helps to better capture the important elements of the distribution of Y_{ijt} by taking into account the potentially skewed distribution of unobserved country-fixed effects, which the correlated random effects (CRE) approach may not fully address as discussed in a later subsection. In most cases, overall model fit is maximized when the Box-Cox transformation parameter λ is close to 0. Under this condition, the transformed dependent variable in equation (6) is approximated by the natural log of Y_{ijt} , $\ln(Y_{ijt})$, so that the double-hurdle models in equations (5) and (6) also become what is known as a two-tiered model (Wooldridge 2002).

Variables Z_i and Z_j include factors that define the Mundlak (1978)-Chamberlain (1984) CRE model. These consist of time-invariant variables including country-specific averages of X_{it} and X_{ijt} , respectively, across the entire study period (1984–2022). Z_i and Z_j also include other time-invariant factors, such as NBS (Mekonnen & Spielman 2021). To account for historical trends in PGRFA exchange behavior, they also include the average number of PGRFA transfers per year from 1961 to 1983 (before the primary focus period of our analysis).

Importantly, equations (5) and (6) assume that NP party status can be treated as exogenous (conditional on CRE terms). We argue that this assumption is reasonable because dependent variables are much more disaggregated—across recipient country level in each year, rather than aggregated at donating-country levels—in equations (5) and (6), which is different from the CSDID analyses that focus on aggregated transfer across all recipient countries for the year.

4.2.1 Count data method

Lastly, we tested our approach of continuous variables model against alternative approaches that model the integer nature of our dependent variables, using Akaike and Bayesian information criteria (AIC and BIC hereafter).¹⁰ While some of the related past studies used count data models for earlier data, our results, which include more recent data, suggest that our double-hurdle (two-

¹⁰ Information criteria have been used to determine whether count data models are better than continuous variable models (see, for example, Akram et al. 2023).

tiered) models appear to be preferable to count data models like CRE-zero-inflated Poisson or CRE-zero-inflated negative binomial models based on AIC and BIC criteria (shown in Appendix B). These diagnostics further support our use of double-hurdle models.

5 Results

5.1 CSDID estimation results

Table 5 presents the results of CSDID analyses based on equations (1) through (4), while Figure 3 provides a visual illustration of the findings. The results indicate that overall, becoming party to the NP has led to a decline in PGRFA provision for certain crops. Although the effects are less deterministic for other crops, NP party status has had negative effects on significant shares of the observed periods.

The most pronounced results are observed for pearl millet and wheat. For pearl millet, the point estimate of the negative coefficient in the “overall effects” column indicates that between 2014 and 2022, NP party status led to an average reduction of 8.6 accessions donated per country per year (at the 10-percent significance level), equivalent to almost 80 percent of the average annual count of donations made in the pre-2014 period by countries that are party to the NP (excluding those that had never made any donations of pearl millet PGRFA). However, this estimate should be interpreted with caution given the large confidence intervals. The adverse effects were particularly significant in 2015, 2017, 2018, and 2019 (in the “calendar time effects” column). The effects in each year are due to a combination of (a) countries newly becoming party to the NP in that particular year, as well as (b) dynamic effects by countries that had become party to the NP in earlier years. The patterns in the “Event study” column indicate that, at the country level, becoming party to the NP has had persistently adverse effects on donating accessions of pearl millet for several years after becoming party. For example, in the first year of becoming party to the NP, the number of pearl millet accessions donated drops by 7.9 (compared to the counterfactual of not becoming party), equivalent to a roughly 75 percent decline compared to their pre-2014 period levels. In the second year of NP membership, the number of accessions donated is still 8.2 lower (compared to the counterfactual). Similar reductions were observed in the third or more years of NP membership. Such persistent dynamic effects may also explain the generally persistent adverse effects that NP had in 2015, 2017, 2018, and 2019. Similarly, for wheat, becoming party to NP has had significantly adverse effects overall (“overall effects” column), with an average reduction of 5.7 accessions donated per country per year (at the 10-percent significance

level). Unlike pearl millet, where the effects are more consistent, the impact on wheat donations has been more variable across years. The negative effect was particularly strong in 2015 (−18.2 accessions per country) and 2018 (−10.7 accessions per country).

Results for other crops are less decisive but still point toward a generally adverse effect of NP party status on PGRFA provision. While the effects of the NP have been generally insignificant in 2014–2022 for maize, there are some indications that countries experienced significantly more negative effects in the long run, that is, 7 and 8 years after becoming party to the NP (“Event study” column). For beans, rice, and sorghum, the overall effects of becoming an NP member have been less precise on average between 2014–2022, but significantly adverse effects are seen in specific years: 2014 for beans; 2020 for rice; and 2015, 2018, 2020, and 2021 for sorghum (“Calendar time effects” column).

5.1.1 Testing parallel trends and implications for potential anticipatory effects

As mentioned in subsection 0, consistency of the CSDID method requires that the parallel trend assumption holds between NP members and nonmembers after conditioning on observed covariates. Additionally, the presence of a parallel trend is critical for minimizing biases that could otherwise arise from various factors, including potential anticipatory effects (Wang & Cui 2023). For example, if there had been significant anticipatory effects before the NP went into effect in 2014, countries might have moved up their provision of PGRFA to the period right before the NP went into effect, thereby reducing the number of accessions that would be subject to the NP’s stringent ABS provisions. Because moving up the provision of accessions may be more likely (rather than occurring randomly) for countries that subsequently became party to the NP, the estimated effects of the NP could be biased. More generally, the violation of parallel trends would indicate that the effects seemingly associated with the NP are actually caused by factors that would have made countries follow diverging patterns in their provision of accessions regardless of the NP and hence should not be attributed to the NP.

We therefore check the parallel trends between NP member and nonmember countries (Wang & Cui 2023). More specifically, the parallel trend can be confirmed, that is, failed to be rejected, by whether $ATT(g, t)$ for $t - 1, t - 2, \dots$ (extending the definition in Figure 1 backwards to the pre-NP era) are not statistically significantly different from zero.

Table 10 in Appendix C provides suggestive evidence of the parallel trends. Importantly, Table 10 presents the parallel trends test across various periods of time prior to the NP. This is done to make sure that the nonrejection of the null hypothesis, or acceptance of the parallel trends, is not due to the possibility that significant effects during periods closer to the NP are cancelled out by the significant but opposite effects during the earlier periods. Were this the case, the test may erroneously accept the null hypothesis even though the parallel trends would actually be rejected. As is seen in Table 10, p-values for the null hypotheses of parallel trends are very high for all crops and all durations of time prior to the NP, which suggests that parallel trends hold and thus our CSDID results are valid.

5.2 Results based on the CRE double-hurdle model

Next, we explore the findings from our gravity-model analysis based on the CRE double-hurdle model to assess the effects of a recipient country's NP party status. Table 6 presents the results of the gravity-model regressions described in equations (5) and (6).¹¹ The results in Table 6 are generally consistent with the hypotheses that a recipient country becoming party to the NP, as well as provider countries also having NP party status, have broadly adverse effects on PGRFA flows between these countries. Specifically, becoming a party to the NP is negatively associated with the quantity of genetic resource materials donated to genebanks in other countries or to CGIAR for beans, cowpeas, pearl millet, rice, and wheat. Similarly, the NP party status of a recipient country is negatively associated with the amount of genetic resource materials donated to these countries, especially for beans, cowpea, maize, pearl millet, rice, and wheat. These results are consistent with the hypothesis that becoming party to the NP of both donating countries and recipient countries adversely affects international PGRFA flows, suggesting that the potentially negative effects of the NP are fairly robust and hold even when only one of the two countries involved (either the provider or the recipient) is party to the NP.

Table 7 expands these results by examining how the impact of being party to the NP varies depending on the regulatory capacity of both provider and recipient countries. As Figure 2 and **Error! Reference source not found.** illustrate, an increasing share of PGRFA has been received

¹¹The appropriate test for the correlations in error terms between equations (5) and (6) remains unclear in the literature, due to the fact that (6) employs a Box-Cox transformation. Nonetheless, given that the sample sizes for equation (6) are generally only a tiny fraction of the sample sizes for equation (5) (as is shown in Table 6 and Table 7), we argue that the potential correlations between error terms in equations (5) and (6) may be modest.

by LMICs since the NP's introduction in 2014, though regulatory capacity in these countries is lower in overall terms while also exhibiting greater cross-country variation. Thus, our underlying hypothesis is that while the overall effects of becoming a party to the NP (either as a provider country or recipient country) are negative, these adverse effects may be partly mitigated by greater national capacity to implement regulatory measures required by the NP.

The results in Table 7 generally support these hypotheses. For example, the regulatory capacity of a provider country attenuates the effect of becoming a party to the NP on PRGFA flows in a significant share of the regression estimates below, including those for cowpea, pearl millet, rice, and sorghum. Similarly, higher regulatory capacity in recipient countries appears to alleviate the adverse effects of being party to the NP on PGRFA inflows, especially for beans, maize, and pearl millet. The prevalence of such significant and consistent effects enhances the credibility of our argument that the limited national capacity to implement the NP may significantly limit countries from realizing the intended benefits of NP. Importantly, these results supplement the CSDID results described in the previous section, which are ambiguous as to whether countries may adjust over time to minimize the adverse effects of being party to the NP. For example, while the results for beans and wheat in Figure 3 suggest that the adverse effects of the NP generally dissipate over time, results for other crops are more ambiguous, including results for maize and sorghum, in which the adverse effects of the NP may worsen over time. The results from the gravity-model regressions add more nuance to these findings by suggesting that the dynamics of regulatory capacity development may offset the adverse effects of NP membership.

6 Conclusions

Historical accounts of crop science demonstrate that the international exchange of PGRFA is an essential element in crop improvement programs that enhance the productivity of crop varieties to address food security, agrifood system development, and economic growth across most low- and middle-income countries (Spiertz, 2014; Sonnino, 2017). But unlike other natural resources, PGRFA is a global public good: it is a nonrival, nonexcludable commodity of considerable international value, but for which neither private firms nor sovereign governments had the incentive to conserve, exchange, or produce in the absence of a global coordination mechanism. Beginning in the 1950s, that global coordination mechanism was a loose but shared international commitment to the relatively free movement of PGRFA to address hunger and malnutrition that

was later formalized in mechanisms managed by the Food and Agriculture Organization of the United Nations, CGIAR, and a global network of genebanks, national breeding programs, and agricultural research organizations.

Beginning in the 1990s, international legal agreements that govern the conservation, exchange, and use of these resources changed dramatically as a suite of treaties and conventions came into effect. LMIC countries are now navigating a much more complex landscape that accords greater national sovereignty over biological diversity than in past eras; prioritizes access and benefits sharing for countries and communities that have historically conserved biological diversity; and requires the development of considerable regulatory capacity to manage PGRFA exchanges. Despite the significant global political will that has led to these governance changes, there is limited empirical, quantitative evidence on how these agreements and conventions affect the global exchange of PGRFA.

We aim to narrow this knowledge gap by using GENESYS data and other cross-country panel data to explore the effect of the NP on global PGRFA exchanges between countries over time. Our findings indicate that becoming a party to NP generally reduces a country's provision of PGRFA to other countries and to international organizations like CGIAR. These results are relatively more robust for millet and wheat. And while overall results are less precise for beans, maize, rice, and sorghum—due to fluctuations in the effects—we still observe significantly adverse effects across nontrivial shares of the time periods analyzed. Our gravity-model type analyses further show that the provision of PGRFA is negatively associated with a recipient country being a party to the NP. The negative associations for both donating and recipient countries with the NP party status are further exacerbated by the regulatory capacity of either the provider or recipient country.

It is beyond the scope of this paper to undertake a more in-depth assessment of the specific nature of required institutional investments and regulatory capacity improvement, and generalizations of our results to broad aspects of such investments and capacity improvement should be avoided. Nonetheless, these findings are consistent with our two main hypotheses and with concerns voiced by other policy researchers and analysts. First, our findings are consistent with our hypothesis that the 2014 NP has significantly reversed or offset the positive effects of the 2004 ITPGRFA on PGRFA exchanges. Secondly, the regulatory capacity requirements associated

with the NP may discourage PGRFA exchanges, particularly for recipient countries in sub-Saharan Africa and South Asia that comprise the majority of PGRFA recipients over time.

Our findings point to several future recommendations. First, our findings are consistent with the hypothesis that supporting regulatory capacity development in LMICs remains important, although it is beyond the scope of this paper to delve deeper into the specific strategies. Prior studies on these issues point to the need for greater public spending on regulatory capacity, human resource development; streamlining of legal channels, bodies, and recourse measures; alignment of national laws with international agreements and conventions; and awareness creation (see Kuhlmann et al. 2025). The second policy recommendation from our findings suggest a continuing role for international coordination mechanisms such as CGIAR—its genebanks networks and breeding programs as well as its national partnerships in genetic resource conservation and breeding—to ensure the conservation and exchange of PGRFA for the benefit of LMICs (Halewood et al. 2020). Third, there is a need to innovate on how to fund genebanks and breeding programs by, for example, crowding in philanthropic and private sector investment, especially if the downward trend in official development assistance from high-income countries continues (see, for example, Hamann 2026). As suggested by Halewood et al. (2020), there is an urgent need to bolster the multilateral system implemented under the ITPGRFA to ensure that supportive national policies, effective planning and coordination of collaborative projects, and stable long-term funding are available to substantially increase the acquisition and distribution of plant genetic resources for food and agriculture.

Lastly, the evidence provided in this paper motivates broader questions that future studies should address. First, while our analyses focused on major staple crops, the significant effects of the NP on these staple crops raise further questions regarding the broader implications for other crops, including many neglected and underutilized crop species. Despite being important public goods, including for marginalized populations, many of these crops are neither included in the ITPGRFA's Annex 1 List of crops covered under the Multilateral System nor within the CGIAR's mandate. More research is needed on how the global exchanges of these neglected and underutilized PGRFA are affected by the NP and other regulatory regimes. Secondly, our findings on the potential roles of greater regulatory capacity motivate more in-depth assessment of the benefits, including the nonmonetary benefits, afforded to countries by the International Treaties, including the ITPGRFA. While our analyses partly demonstrate the mitigating roles of higher

regulatory capacity, our measures are still crude, and future analyses require finer measures of the regulatory capacity that capture its multi-faceted nature. Third, while the GENESYS data allowed us to capture the movement of PGRFA across genebanks, further processing and compilation of data could capture the effects on broader aspects involving the PGRFA (Mekonnen & Spielman 2021). These may include the PGRFA movement between breeding programs or effects at more downstream levels, such as genetic diversity, improved materials, elite lines, and finished varieties that end up being used by breeders.

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Table 1. Annual average number of genebank accessions of selected crops by major genebanks in the Pre-CBD, CBD, ITPGRFA and NP decades (count per year)

	Beans	Maize	Pearl millet	Rice	Sorghum	Wheat
CGIAR genebanks						
Pre-CBD (1984-1993)	NA	NA	1,007	3,150	1,124	5,576
CBD (1994-2003)	NA	NA	397	2,728	310	3,776
ITPGRFA (2004-2013)	NA	NA	221	2,100	284	3,170
NP (2014-2022)	NA	NA	399	859	695	1,698
US genebanks						
Pre-CBD (1984-1993)	284	928	62	264	1,199	758
CBD (1994-2003)	260	547	8	176	371	954
ITPGRFA (2004-2013)	386	423	27	3,216	243	489
NP (2014-2022)	11	8	0	0	0	2
Genebanks in the rest of the world						
Pre-CBD (1984-1993)	94	926	23	1,133	385	5,131
CBD (1994-2003)	262	1,260	43	969	366	3,689
ITPGRFA (2004-2013)	211	921	74	597	306	3,398
NP (2014-2022)	81	377	348	2,197	596	5,714
Total						
Pre-CBD (1984-1993)	378	1,854	1,092	4,547	2,708	11,465
CBD (1994-2003)	522	1,807	448	3,873	1,047	8,419
ITPGRFA (2004-2013)	597	1,344	322	5,913	833	7,057
NP (2014-2022)	92	385	747	3,056	1,291	7,414

Source: Authors for NP (2014-2022) period; Mekonnen & Spielman (2021) for other periods. NA denotes “Not Applicable.”

Note: Some figures have been updated since Mekonnen & Spielman (2021), due to the updating of GENESYS record.

Table 2. Network size changes of genebank accessions in the pre-CBD, CBD, ITPGRFA and NP decades of selected crops

	Beans	Maize	Pearl millet	Rice	Sorghum	Wheat
CGIAR genebanks						
Pre-CBD (1984-1993)	NA	NA	47	105	56	112
CBD (1994-2003)	NA	NA	34	46	38	79
ITPGRFA (2004-2013)	NA	NA	13	121	12	88
NP (2014-2022)	NA	NA	41	83	61	67
US genebanks						
Pre-CBD (1984-1993)	47	80	21	64	79	76
CBD (1994-2003)	31	38	8	43	21	40
ITPGRFA (2004-2013)	62	28	4	77	18	31
NP (2014-2022)	3	2	0	0	0	5
Genebanks in the rest of the world						
Pre-CBD (1984-1993)	45	60	21	75	48	116
CBD (1994-2003)	49	60	31	41	63	107
ITPGRFA (2004-2013)	28	58	19	37	68	101
NP (2014-2022)	9	49	46	36	52	114

Source: Authors for NP (2014-2022) period; Mekonnen & Spielman (2021) for other periods. NA denotes “Not Applicable.”

Note: Some figures have been updated since Mekonnen & Spielman (2021), due to the updating of GENESYS record.

Table 3. Descriptive statistics of control variables (all countries-years aggregated, based on the World Bank income classes)^a

<i>Variable</i>	All	Low Income	Lower- Middle	Upper- Middle	High	Source
	mean (std.dev)	mean	mean	mean	Mean	
Cultivated area (ha) of each crop (natural log)						FAOSTAT
Beans	5.642 (5.332)	7.463	6.770	5.708	2.910	
Cowpea	1.554 (3.752)	3.547	1.408	0.815	0.477	
Maize	8.543 (5.381)	11.293	9.198	8.394	6.043	
Pearl millet	3.853 (5.197)	8.173	3.237	2.394	1.633	
Rice	6.359 (5.881)	10.164	7.177	5.449	2.875	
Sorghum	5.146 (5.468)	8.626	5.510	4.326	2.348	
Wheat	6.690 (6.155)	6.428	6.452	6.762	8.187	
the presence of access and benefit sharing (ABS) regulations	0.083 (0.276)	0.045	0.060	0.094	0.153	Mekonnen & Spielman (2021)
GDP per capita (2015 USD, '000)	11.740 (18.988)	0.827	2.959	8.348	37.613	World Bank (2024)
Trade openness	0.834 (0.504)	0.623	0.819	0.859	1.044	World Bank (2024)
<i>CRE-only variables (Time-invariant)</i>						
Regulatory quality index	−0.089 (0.982)	−0.905	−0.493	−0.036	1.120	World Bank (2024b)
Agricultural R&D spending from <u>ASTI</u>	0.257 (0.682)	0.094	0.173	0.315	0.663	ASTI (2024); Nin-Pratt (2021); Heisey & Fuglie (2018) for high-income countries
Agricultural IPR	1.849 (1.410)	1.186	1.711	2.231	2.633	Campi & Nuvolari (2021)
National biodiversity score	0.550 (0.159)	0.577	0.579	0.593	0.447	Mekonnen & Spielman (2021)
Historical averages of annual count (1961-1980)						
Beans	8.882 (34.037)	2.416	9.901	20.247	5.991	GENESYS
Maize	2.245 (9.782)	0.786	1.196	3.728	4.009	
Pearl Millet	1.092 (5.107)	2.572	0.785	0.862	0.182	
Rice	20.417 (76.315)	34.844	29.963	10.034	5.565	
Sorghum	7.147 (31.567)	17.484	5.668	2.319	3.000	
Wheat	14.891 (41.920)	13.942	10.068	17.669	19.653	

Source: Authors' compilations from various sources indicated in the table.

Notes: ^a Samples are grouped into each income classes, which also vary across years. For example, if a country is in Low Income until 2000 and moved to Lower Middle Income, the data for this country up to 2000 are included in Low Income sample, and the data from 2021 are included in Lower Middle-Income sample. Statistics are calculated by pooling all samples in each income class.

Table 4. Number of countries by the year of becoming NP signatories (total countries in sample = 191)

Year	Number of countries newly becoming NP parties	Cumulative number of NP party countries
2014	52	52
2015	15	67
2016	17	84
2017	16	100
2018	9	109
2019	10	119
2020	7	126
2021	4	130
2022	6	136

Source: Authors' compilations from <https://www.cbd.int/abs/nagoya-protocol/signatories>

Table 5. Callaway-Sant’Anna DID method

Crops	Overall effects	Calendar time effects ^a		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019	t=2020	t=2021	t=2022
		Event study ^b	Aggregated effects	e=0	e=1	e=2	e=3	e=4	e=5	e=6	e=7	e=8
Beans	-0.341 (0.509)	Calendar time effects	-0.749 (0.543)	-7.553*** (1.441)	0.471 (0.565)	N/A	N/A	0.420 (0.503)	0.420 (0.503)	0.433 (0.504)	0.154 (0.474)	0.411 (0.462)
		Event study	-0.245 (0.507)	-4.892*** (1.472)	0.136 (0.293)	0.024 (0.074)	0.780 (0.723)	0.420 (0.503)	0.275 (0.556)	0.413 (0.499)	0.456 (0.617)	0.182 (0.386)
Maize	-22.439 (21.059)	Calendar time effects	-18.153 (18.389)	2.098 (7.664)	0.272 (4.438)	1.918 (6.104)	-1.381 (3.701)	-33.953 (46.307)	9.497 (7.785)	-94.805 (67.973)	-28.867 (35.667)	N/A
		Event study	-43.837* (26.492)	14.481 (12.722)	8.451 (10.492)	20.530 (12.780)	-5.140 (22.175)	-18.541 (45.589)	-10.866 (33.808)	-149.632** (75.492)	-209.978** (89.270)	N/A
Pearl Millet	-8.550* (5.013)	Calendar time effects	-9.097* (5.367)	-13.165 (8.793)	-11.448* (6.473)	-7.885 (5.261)	-7.834* (4.553)	-9.594** (4.730)	-9.521** (4.705)	-4.231 (3.890)	N/A	N/A
		Event study	-8.648* (5.375)	-7.948* (4.235)	-8.221* (4.297)	-8.749** (4.480)	-7.569* (4.495)	-8.817* (5.350)	-11.621* (6.496)	-7.613 (9.586)	N/A	N/A
Rice	-0.575 (0.399)	Calendar time effects	-0.331 (0.393)	3.074*** (1.019)	1.753 (2.049)	0.690 (2.247)	-8.119 (5.394)	-4.388 (7.823)	0.576 (1.109)	-0.964* (0.517)	4.490 (4.222)	-0.094 (1.052)
		Event study	-0.477 (0.350)	0.662** (0.266)	-1.778* (0.945)	1.361** (0.675)	-6.590** (2.578)	-0.674 (4.008)	1.078* (0.604)	3.274 (2.850)	-1.780* (1.077)	0.155 (0.811)
Sorghum	-1.439 (1.528)	Calendar time effects	-1.667 (1.880)	-2.333 (6.555)	-8.345* (5.075)	0.603 (0.386)	12.494* (6.441)	-7.246* (4.583)	N/A	-1.249* (0.694)	-5.594* (3.426)	N/A
		Event study	-1.841 (1.580)	-0.258 (2.686)	0.123 (1.351)	-0.062 (0.166)	6.482* (3.810)	-7.299* (4.508)	-1.272*** (0.424)	-2.307* (1.424)	-10.600* (6.226)	N/A
Wheat	-5.714* (3.292)	Calendar time effects	-9.512*** (3.548)	-39.815 (27.818)	-18.264* (10.995)	-25.252 (17.109)	-7.055 (7.918)	-10.668* (6.156)	-6.902 (9.537)	-8.096 (8.309)	-9.459 (10.053)	39.902 (51.429)
		Event study	-12.527 (8.709)	-25.708** (13.104)	-13.214*** (3.026)	-15.034 (10.622)	-11.267 (8.495)	-3.163 (10.406)	-1.637 (11.244)	-21.498 (20.201)	-10.409 (17.718)	N/A

Source: Authors’ estimations. ***1% **5% *10%.

Notes: “N/A” for rows other than “Overall effects” are due either to the lack of reported accessions for that year, or the absence of countries that changed either their NP member status or changes in the number of accessions donated from the prior year.

^a Calendar time effects (overall effects of NP in each year): how cumulative ATT evolves over calendar time, from the year when the first group of countries become NP party; ATT for each year (2014 ~), across all groups or cohorts (i.e., across NP party and nonparty in a specific year).

^b Event study (country-level dynamics in ATT): how ATT varies with the length of exposure to the treatment (length of being NP party member) (event-study-type estimands) for each country once the country becomes NP party. ATT’s are estimated for each period relative to the period first treated, across all cohorts.

Table 6. Correlated-Random Effects Double Hurdle Model (with natural-log transformation of non-zero dependent variables)

Variables	Beans		Cowpea		Maize		Pearl millet		Rice		Sorghum		Wheat	
	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.
Party to Nagoya Protocol (NP)	-3.377*** (0.226)	N/A	-0.148** (0.075)	N/A	0.032 (0.075)	0.216 (0.290)	-0.081* (0.047)	0.331 (0.248)	-0.148** (0.075)	N/A	-0.048 (0.079)	-0.080 (0.305)	-0.109** (0.048)	-0.128 (0.113)
Recipient country NP Party	-2.531*** (0.495)	N/A	-3.809*** (0.322)	N/A	-0.641*** (0.226)	-0.348 (0.415)	-6.858*** (0.587)	N/A	-3.809*** (0.322)	N/A	0.110 (0.401)	-0.368 (0.357)	-0.426** (0.206)	-1.388*** (0.202)
NP decade dummy	-1.029*** (0.258)	-1.347*** (0.201)	-1.018*** (0.321)	-0.308 (0.384)	-0.492** (0.207)	-0.452*** (0.175)	-5.433*** (0.419)	-1.193*** (0.259)	-1.018*** (0.321)	-0.308 (0.384)	-0.646*** (0.215)	-0.643** (0.259)	-0.574*** (0.179)	-0.002 (0.076)
ITPGRFA decade dummy	-0.330** (0.125)	0.137 (0.175)	-0.585*** (0.123)	-0.597*** (0.176)	-0.278 (0.076)	-0.083 (0.123)	-0.518*** (0.419)	-0.060 (0.288)	-0.585*** (0.123)	-0.597*** (0.176)	-0.364*** (0.131)	-0.236 (0.153)	-0.303*** (0.068)	-0.283*** (0.046)
CBD decade dummy	-0.181** (0.084)	-0.268* (0.139)	-0.229** (0.114)	-0.024 (0.140)	-0.034 (0.071)	-0.101 (0.101)	-0.116 (0.131)	-0.903*** (0.221)	-0.229** (0.114)	-0.024 (0.140)	-0.232** (0.118)	-0.103 (0.152)	-0.259*** (0.059)	-0.158*** (0.045)
2020 decade dummy	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes		
Log of area under crop														
ABS policy in place														
UPOV membership														
Ln per capita GDP														
Trade Openness														
Linear trend														
Country pair characteristics														
Correlated Random Effects (Country-specific averages over time) of origin country / recipient country														
Log of crop area	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes		
ABS policy														
UPOV														
Per capita GDP														
RD														
AgIPR														
Trade Openness														
Regulatory quality index														
Average count before 1980														
Constant	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes		
Observations	1,370,616	628	1,370,616	580	1,370,616	1,203	1,370,616	430	1,370,616	1,786	1,370,616	931	1,370,616	5,073
p-value for overall insignificance	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

Source: Authors' estimations. ***1% **5% *10%.

Notes: RC = Regulatory capacity.

^a "N/A" indicate no coefficients are estimated due to the absence of sufficient variations conditional on other variables included.

Table 7. Correlated-Random Effects Double Hurdle Model (with natural-log transformation of non-zero dependent variables)^a

Variables	Beans		Cowpea		Maize		Pearl millet		Rice		Sorghum		Wheat	
	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.	Probit	Trunc. Reg.
Party to Nagoya Protocol (NP)	-3.565*** (0.234)	N/A	-1.417*** (0.406)	-0.018 (0.343)	0.025 (0.073)	-0.118 (0.479)	-0.109** (0.055)	0.314 (0.268)	-0.192*** (0.071)	0.098 (0.274)	-0.086 (0.073)	0.402 (0.395)	-0.118** (0.050)	-0.391** (0.192)
Recipient country NP Party	-2.429*** (0.305)	N/A	-2.254 (1.465)	N/A (0.221)	-0.746*** (0.221)	-5.805** (2.787)	-4.923*** (0.534)	N/A	0.327 (0.266)	-1.281* (0.701)	0.097 (0.399)	-4.176* (2.338)	-0.431* (0.263)	-2.360*** (0.872)
NP decade dummy	-1.186*** (0.251)	0.014 (0.711)	-0.954*** (0.338)	-0.943** (0.426)	-0.513** (0.213)	-0.779*** (0.265)	-4.343*** (0.161)	1.366 (1.805)	-0.543** (0.215)	-0.804*** (0.187)	-0.593*** (0.229)	-0.679** (0.316)	-0.535*** (0.177)	-0.231** (0.101)
ITPGRFA decade dummy	-0.306** (0.123)	0.102 (0.172)	-0.520*** (0.173)	-0.669*** (0.183)	-0.289*** (0.079)	0.006 (0.186)	-0.503*** (0.134)	-0.118 (0.280)	-0.170 (0.116)	-0.507*** (0.129)	-0.310** (0.137)	-0.285 (0.200)	-0.256*** (0.067)	-0.515*** (0.062)
CBD decade dummy	-0.137 (0.087)	-0.253* (0.144)	-0.185 (0.128)	-0.085 (0.162)	-0.036 (0.072)	-0.278** (0.122)	-0.122 (0.127)	-1.065*** (0.225)	-0.533*** (0.124)	0.220 (0.134)	-0.193 (0.131)	-0.161 (0.161)	-0.211*** (0.059)	-0.291*** (0.055)
NP party*RC in donating country	-0.105 (0.094)	N/A	0.420*** (0.099)	0.323 (0.498)	-0.170 (0.158)	-0.410 (0.630)	0.062 (0.111)	0.697** (0.344)	0.337** (0.148)	0.315 (0.468)	0.087 (0.122)	1.669** (0.744)	-0.059 (0.074)	-0.488 (0.377)
NP party*RC in recipient country	1.549*** (0.313)	N/A	0.341 (0.345)	N/A	1.247** (0.528)	-0.542 (1.714)	0.180 (0.163)	3.765* (2.052)	0.261 (0.509)	-1.681 (1.516)	0.069 (0.547)	-5.205 (3.831)	0.115 (0.370)	-0.876 (0.779)
Same additional controls as in Table 6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country pair characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,370,616	628	1,370,616	580	1,370,616	1,203	1,370,616	430	1,370,616	1,786	1,370,616	931	1,370,616	5,073
p-value for overall insignificance	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

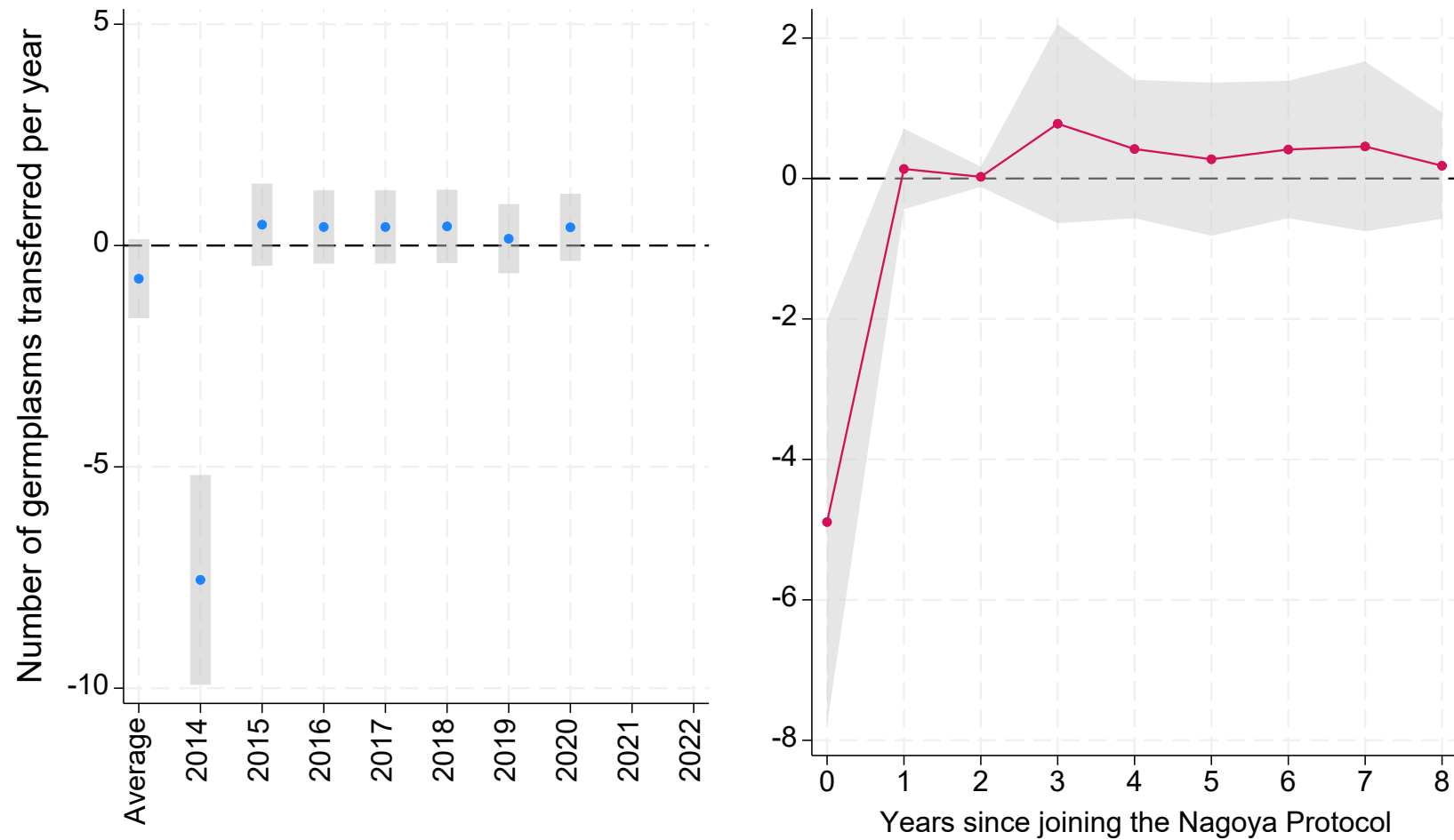
Source: Authors' estimations. ***1% **5% *10%.

Notes: RC = Regulatory capacity.

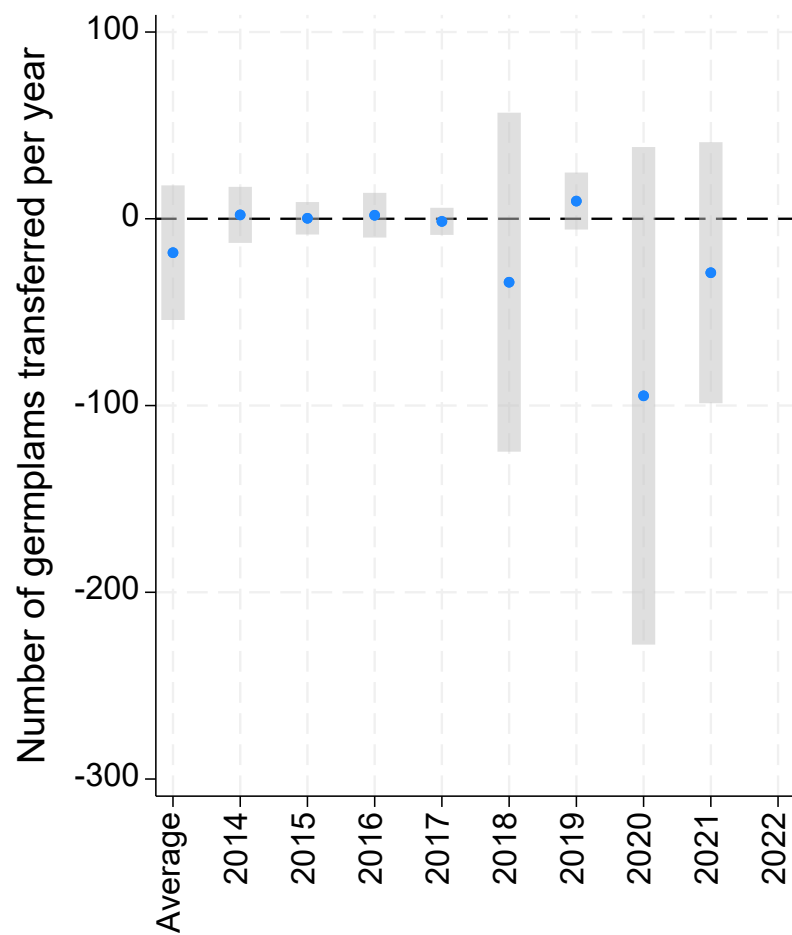
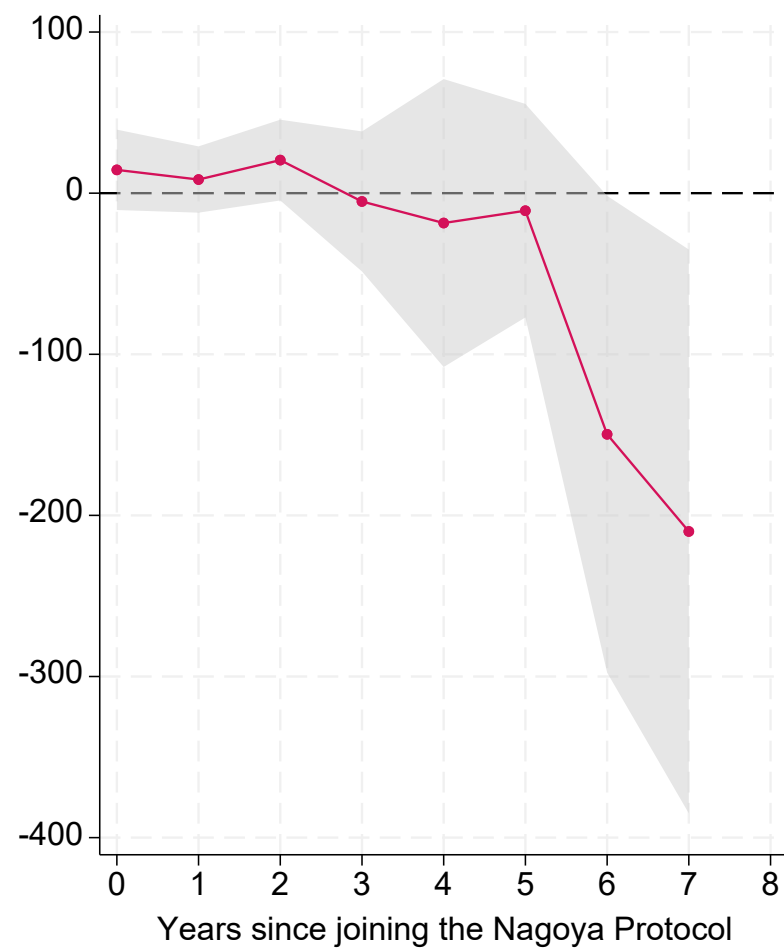
^a "N/A" indicate no coefficients are estimated due to the absence of sufficient variations conditional on other variables included.

Figure 3. (Left panel) ATT of joining the Nagoya Protocol on the number of accessions donated per country in corresponding year (corresponding to the Calendar-time effects in Table 5); (Right panel) country-level changes in ATT over time after joining the NP (“Event study” in Table 5)

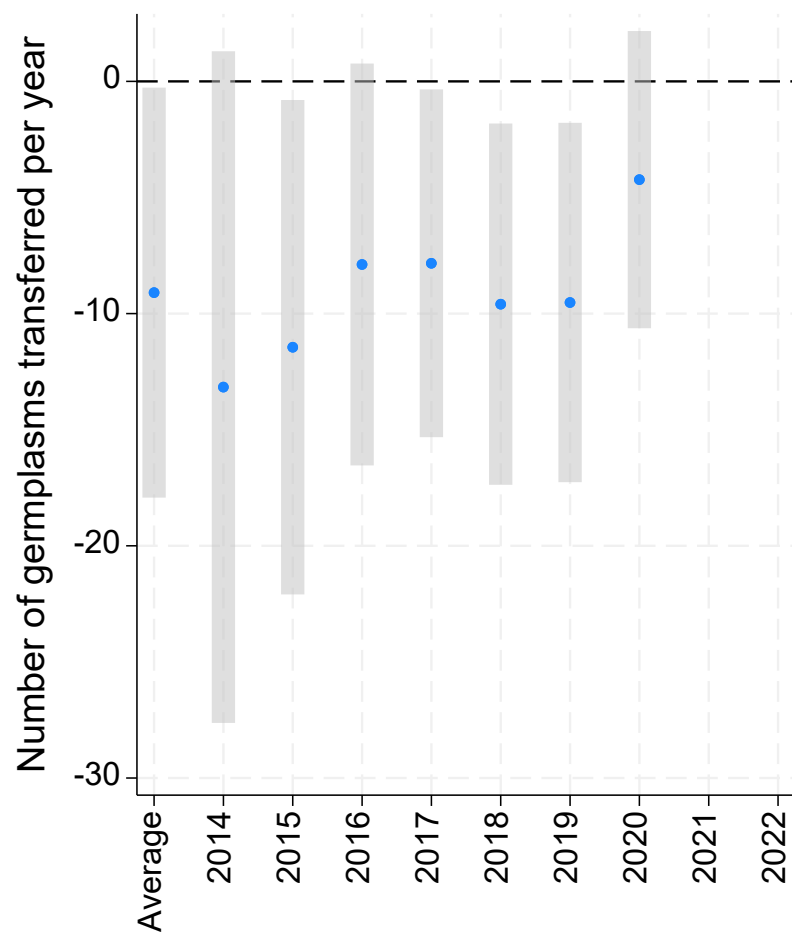
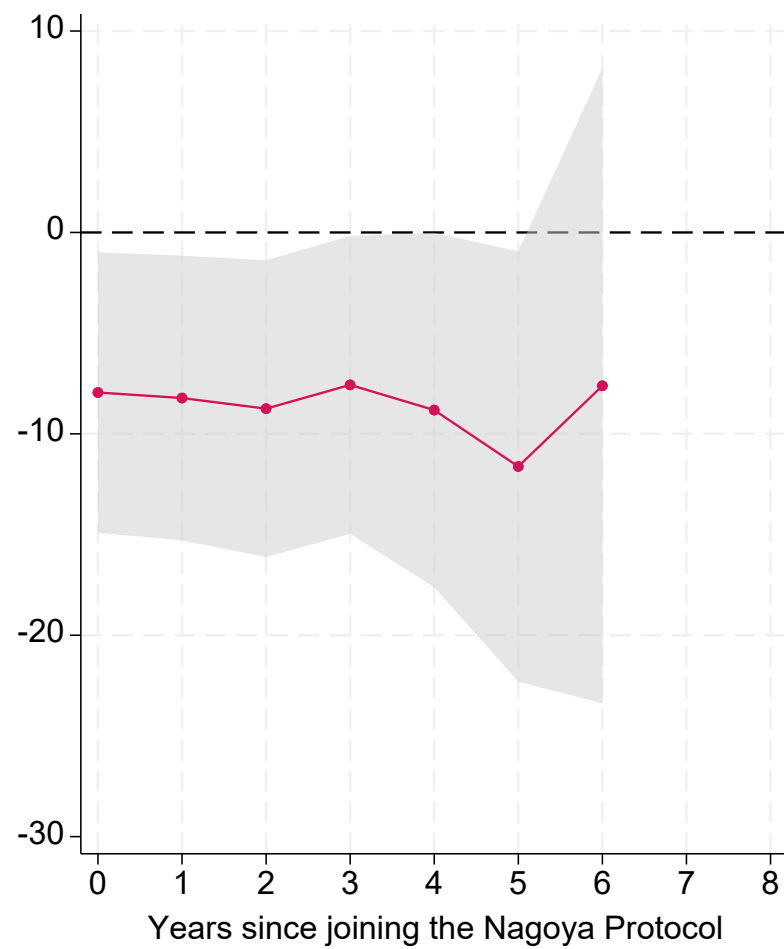
Beans



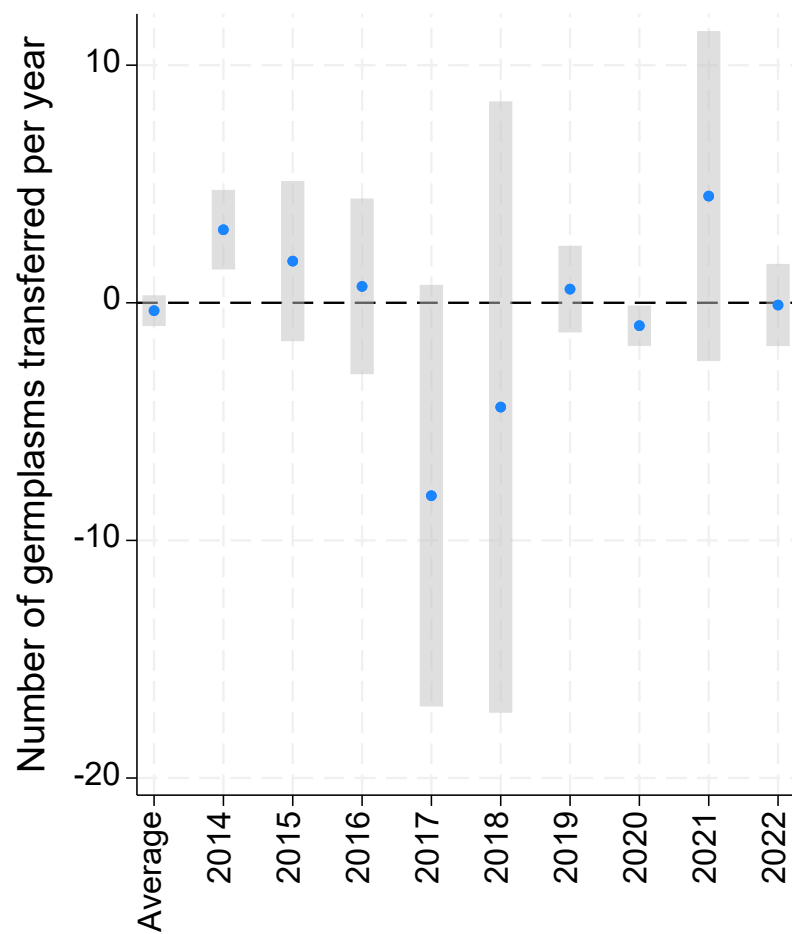
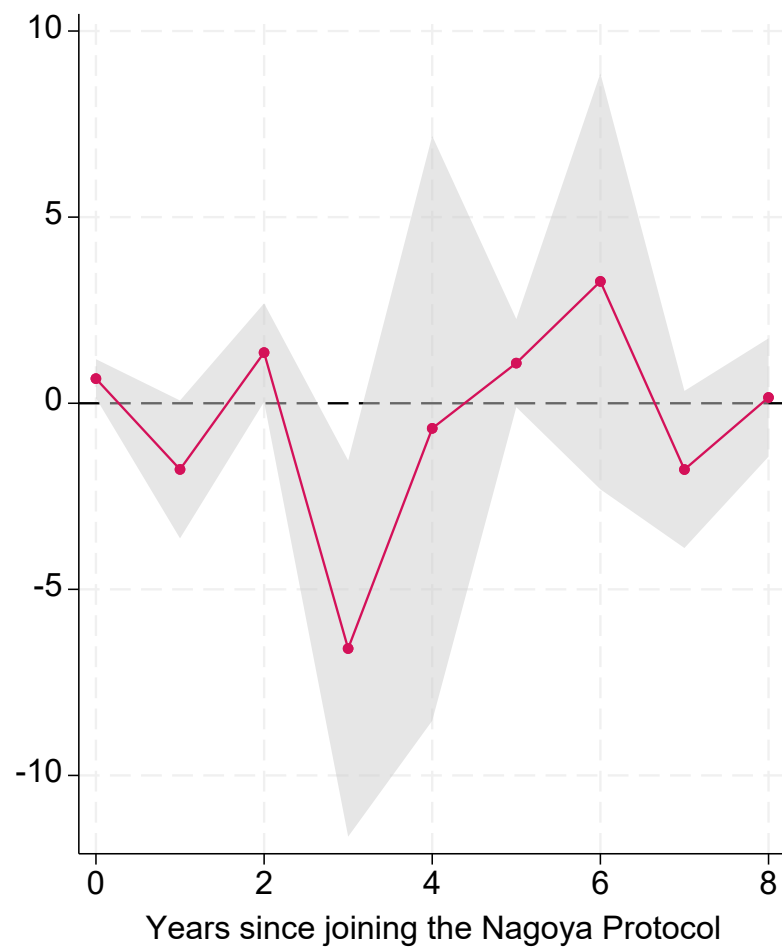
Maize



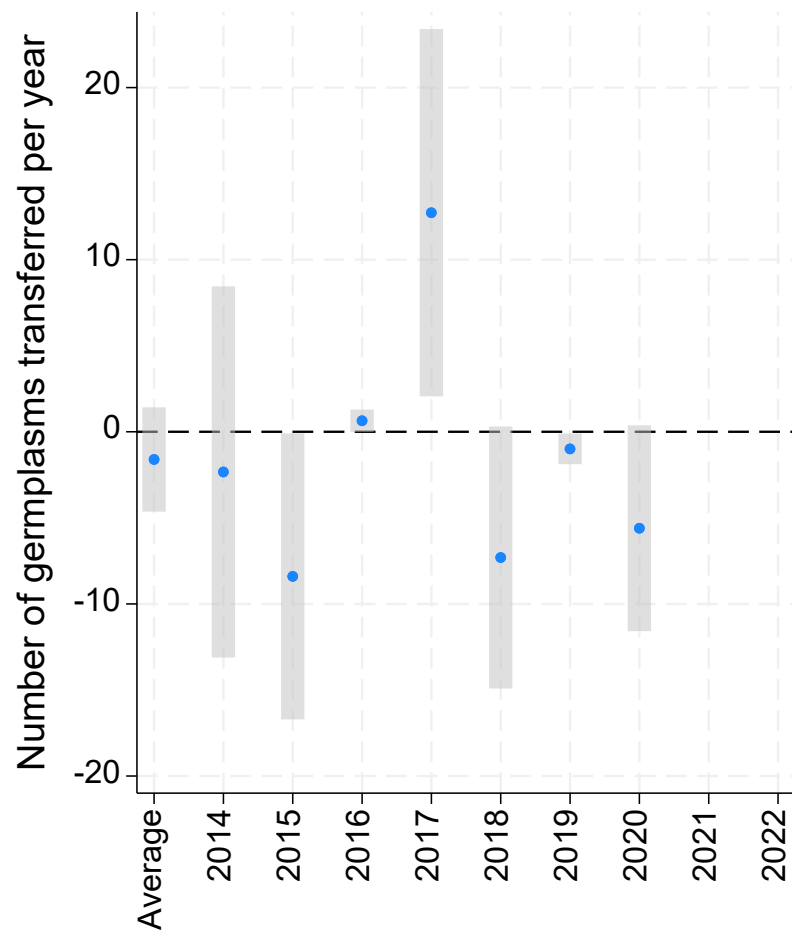
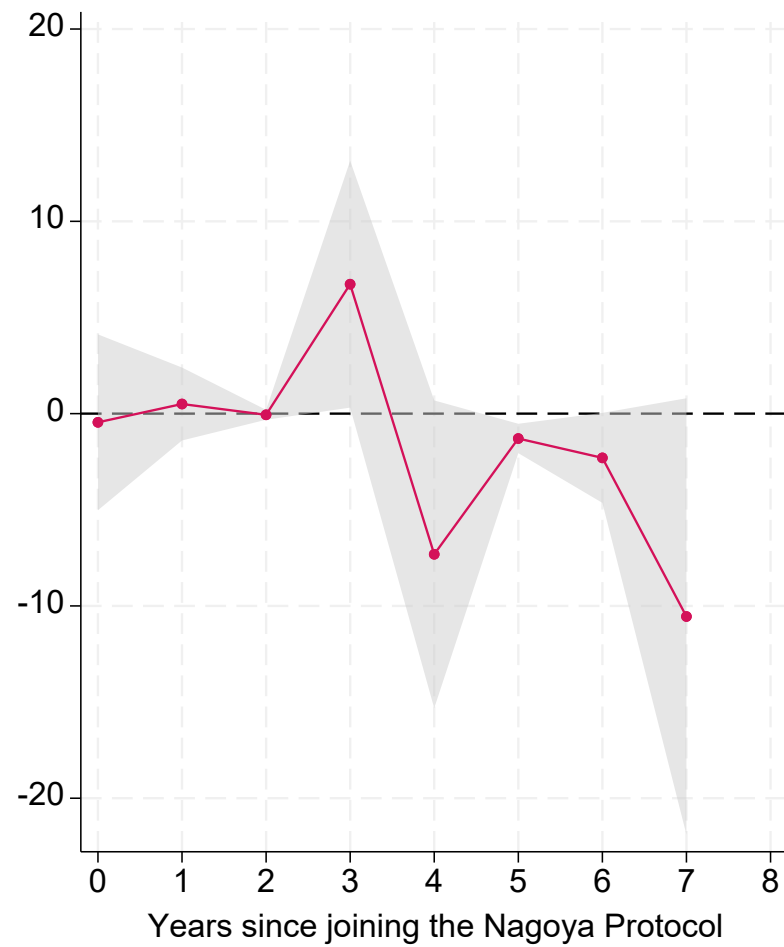
Millet



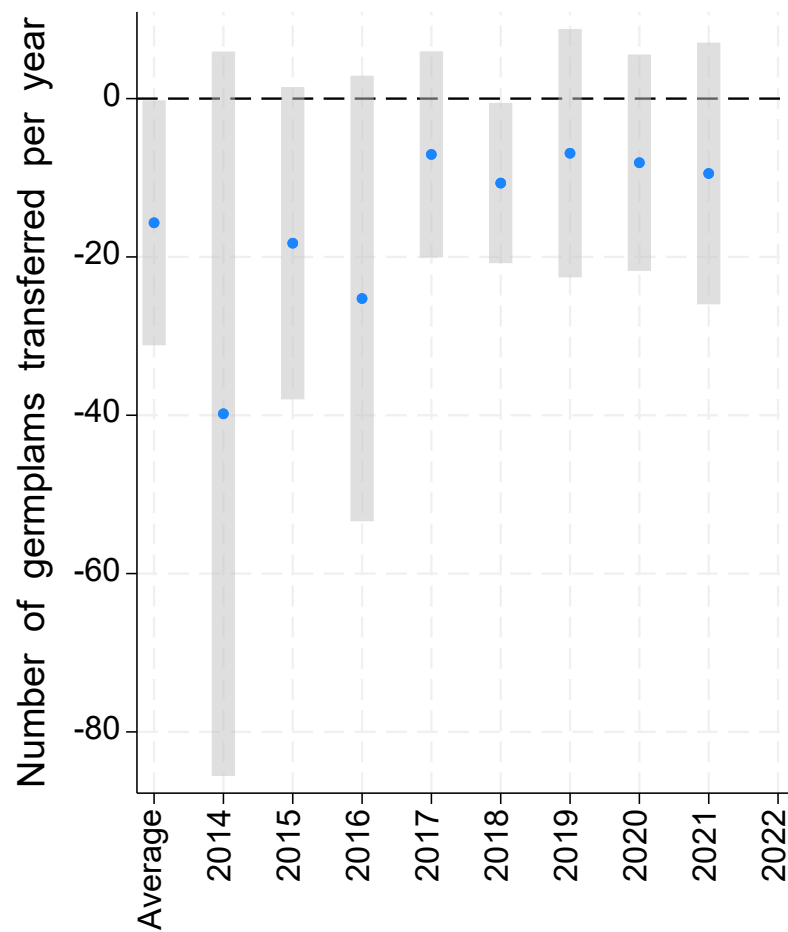
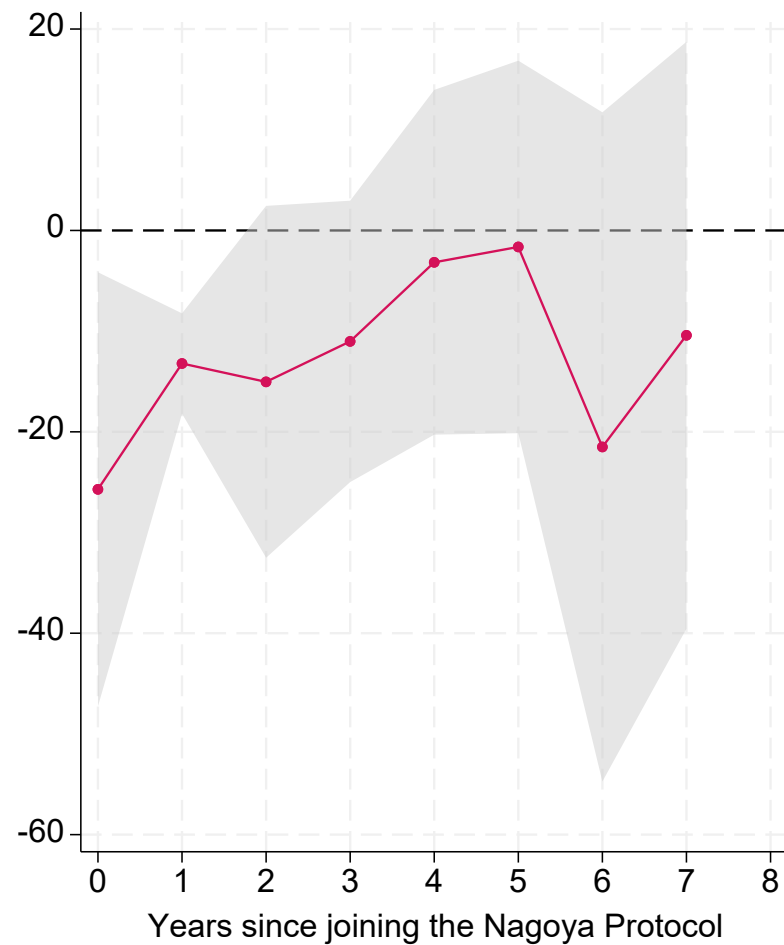
Rice



Sorghum



Wheat



Source: Authors' estimations.

Note: Gray areas indicate 95% confidence intervals for each year. Dots and lines indicate the ATT and their trends.

Appendix A

Based on the panel serial correlation test (Drukker 2003; Wooldridge 2002) (albeit on standard fixed-effects model), first-order autocorrelation is not present except cowpeas (Table 8). Therefore, our DID results are consistent, which can sometimes be biased under severe serial correlation (see, for example, Bertrand et al. 2004).

Table 8. Wooldridge (2002) test of serial correlations

Crops	p-value (H_0 : no first-order auto-correlation based on Wooldridge test)
Beans	.341
Maize	.188
Millet	.471
Rice	.133
Sorghum	.476
Wheat	.532

Source: Authors.

Appendix B

Table 9. Akaike and Bayesian Information Criteria on different model specifications

Models	Criteria	Beans	Maize	Pearl millet	Rice	Sorghum	Wheat
Double-Hurdle (Two-tiered) model (with CRE)	AIC	1,951	3,741	1,150	4,363	2,363	7,623
	BIC	2,199	3,996	1,404	4,650	2,617	7,877
Tobit model (with CRE)	AIC	7,751	14,418	5,144	18,335	9,646	31,525
	BIC	7,872	14,523	5,274	18,489	9,775	31,656
Zero-Inflated Negative Binomial (with CRE)	AIC	6,515	11,751	4,006	12,985	7,633	22,356
	BIC	6,767	12,005	4,258	13,272	7,919	22,604
Zero-Inflated Poisson (with CRE)	AIC	39,414	116,273	32,122	176,362	76,846	329,498
	BIC	39,659	116,521	32,368	176,675	77,125	329,746

Source: Authors. CRE = Correlated Random Effects; AIC = Akaike Information Criteria; BIC = Bayesian Information Criteria.

Note: Lower values of AIC and BIC indicate better overall fit of the models.

Appendix C: Robustness check against potential anticipatory effects

Table 10. Hypothesis testing of parallel trends

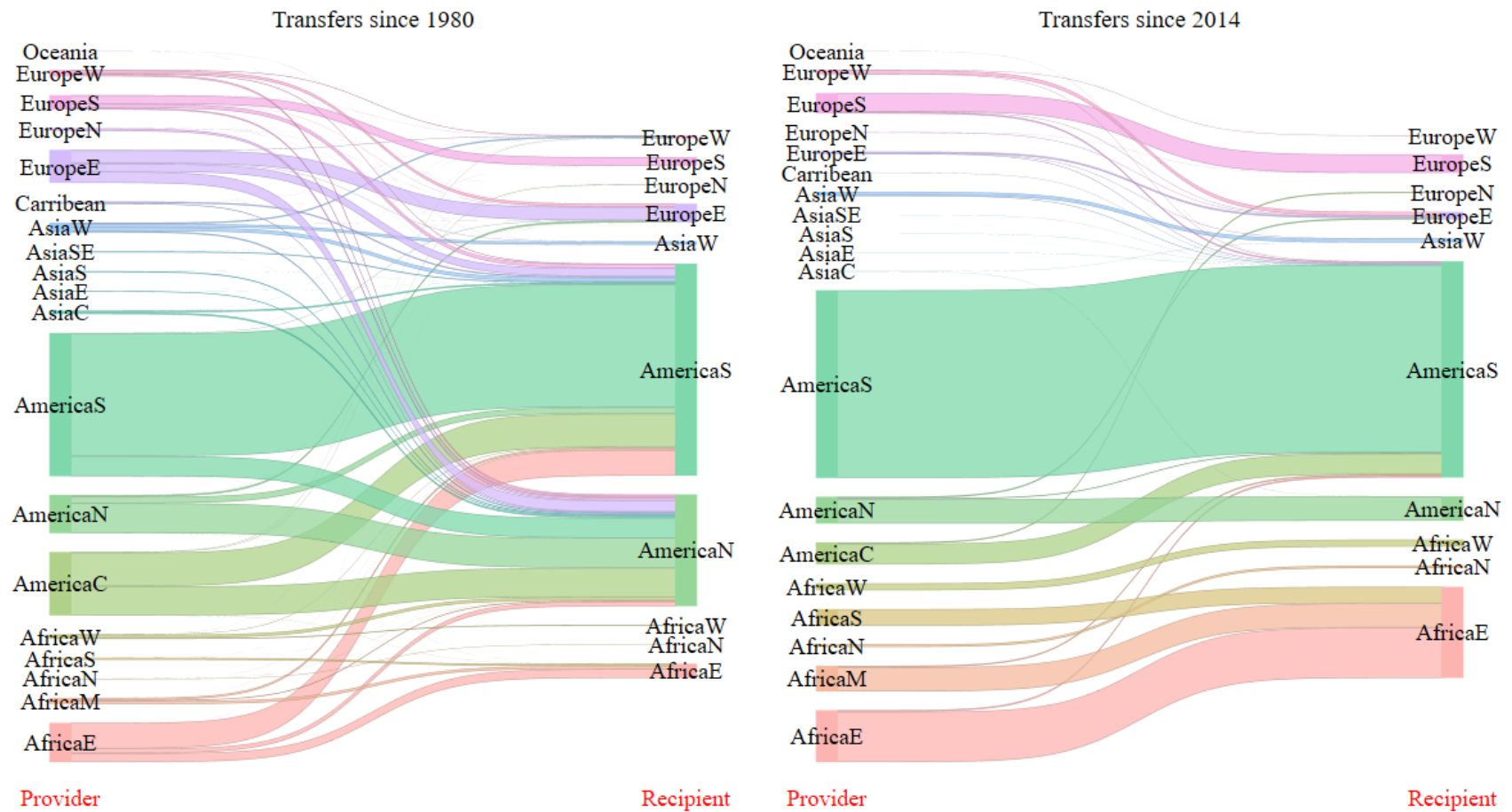
Crops	p-value (H ₀ : Parallel trends hold and there are no anticipatory effects)					
	All period up to the year the country become NP member	Samples post 2004 up to the year the country become NP member	Samples between 2009 up to the year the country become NP member	Samples between 2010 up to the year the country become NP member	Samples between 2011 up to the year the country become NP member	Samples between 2012 up to the year the country become NP member
Beans	1.000	1.000	1.000	.842	.842	.842
Maize	1.000	.996	.833	.512	.512	.512
Pearl millet	1.000	1.000	1.000	1.000	1.000	1.000
Rice	1.000	1.000	1.000	1.000	1.000	1.000
Sorghum	1.000	1.000	.996	.937	.937	.937
Wheat	1.000	1.000	1.000	.999	.999	.999

Source: Authors.

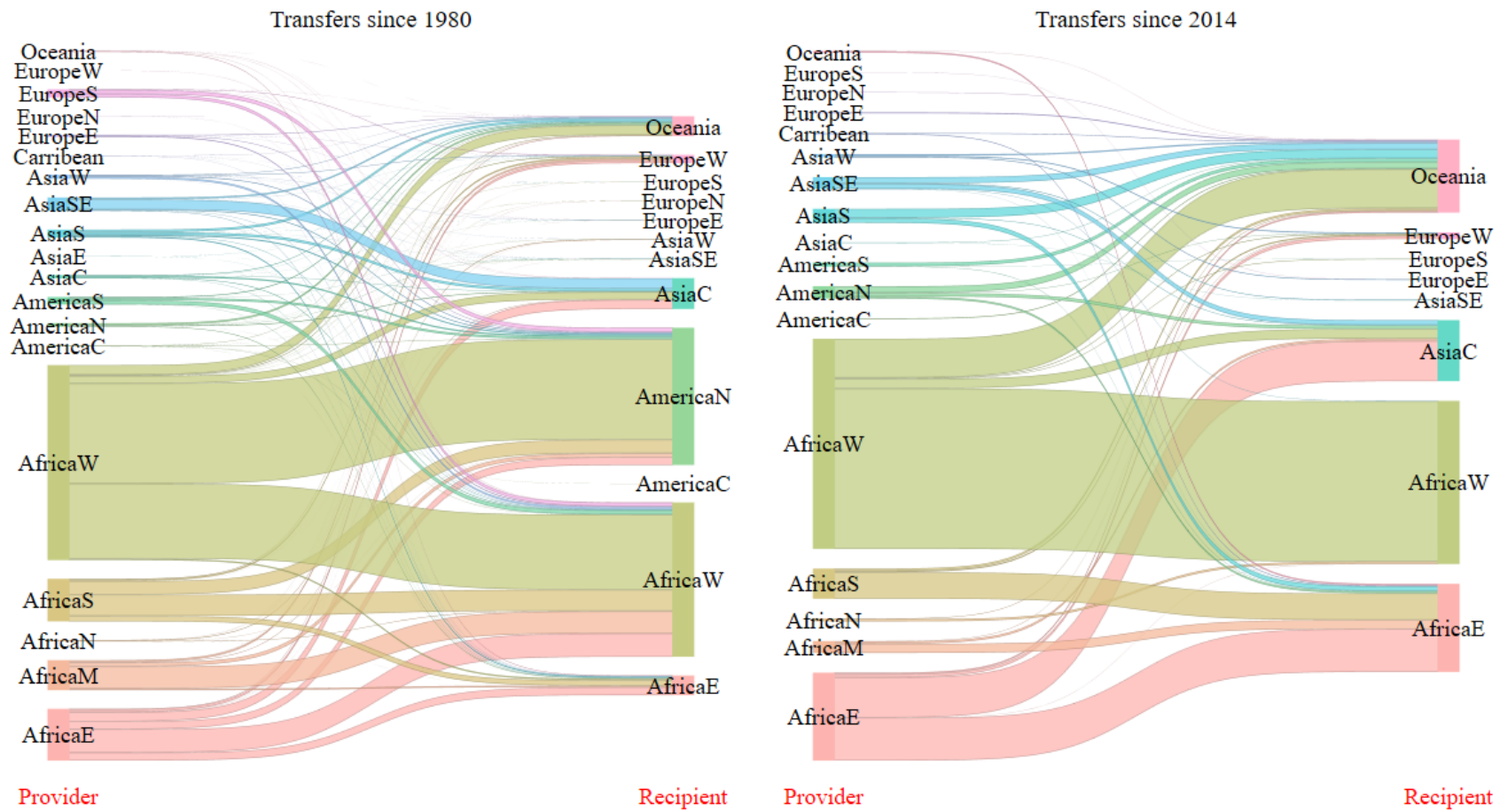
Appendix D: Additional Figures

Figure 4. Sankey diagrams illustrating PGRFA provider and recipient countries, by region, crop, and periods (1980~2023 and 2014~2023).

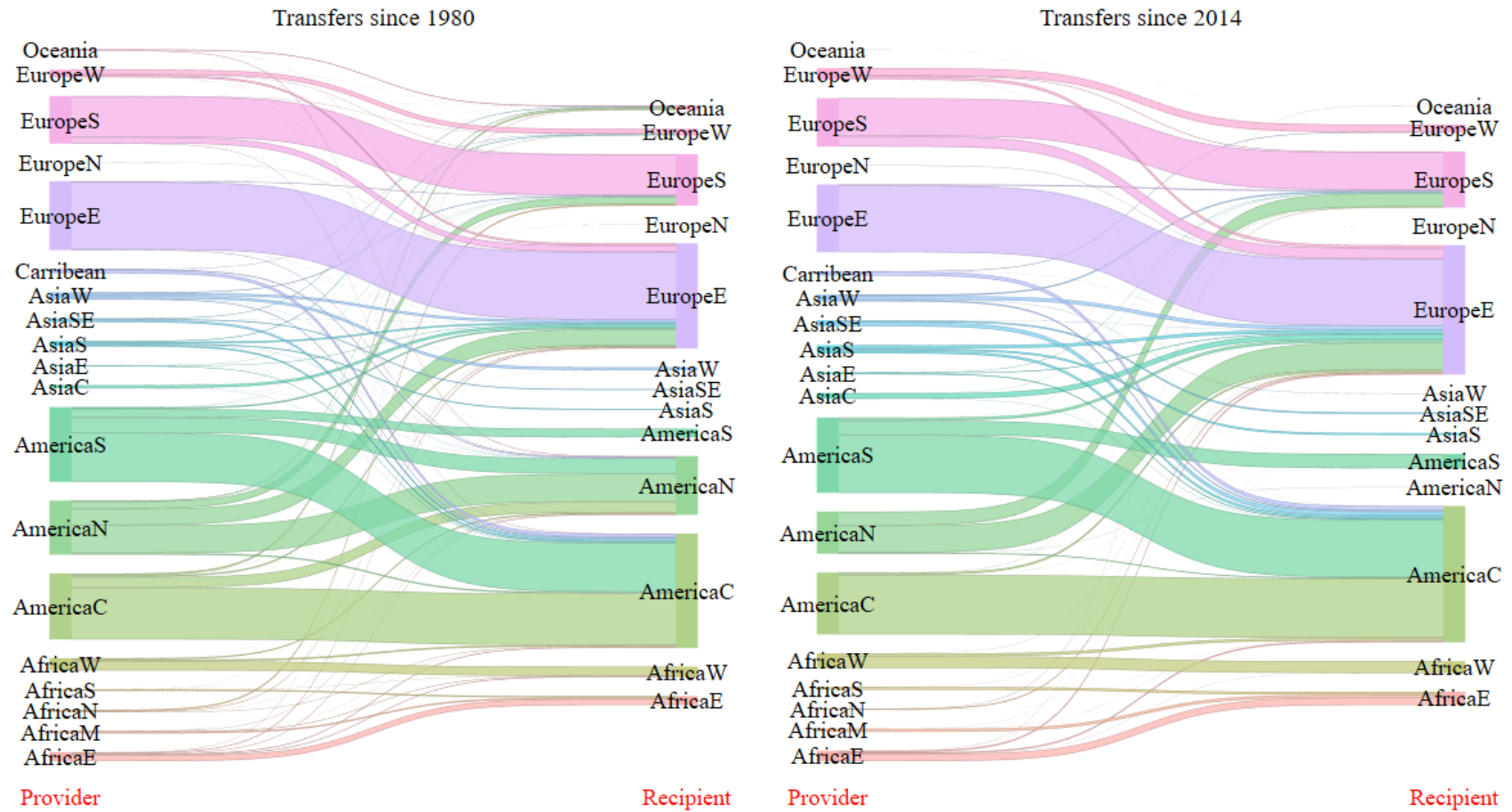
Beans



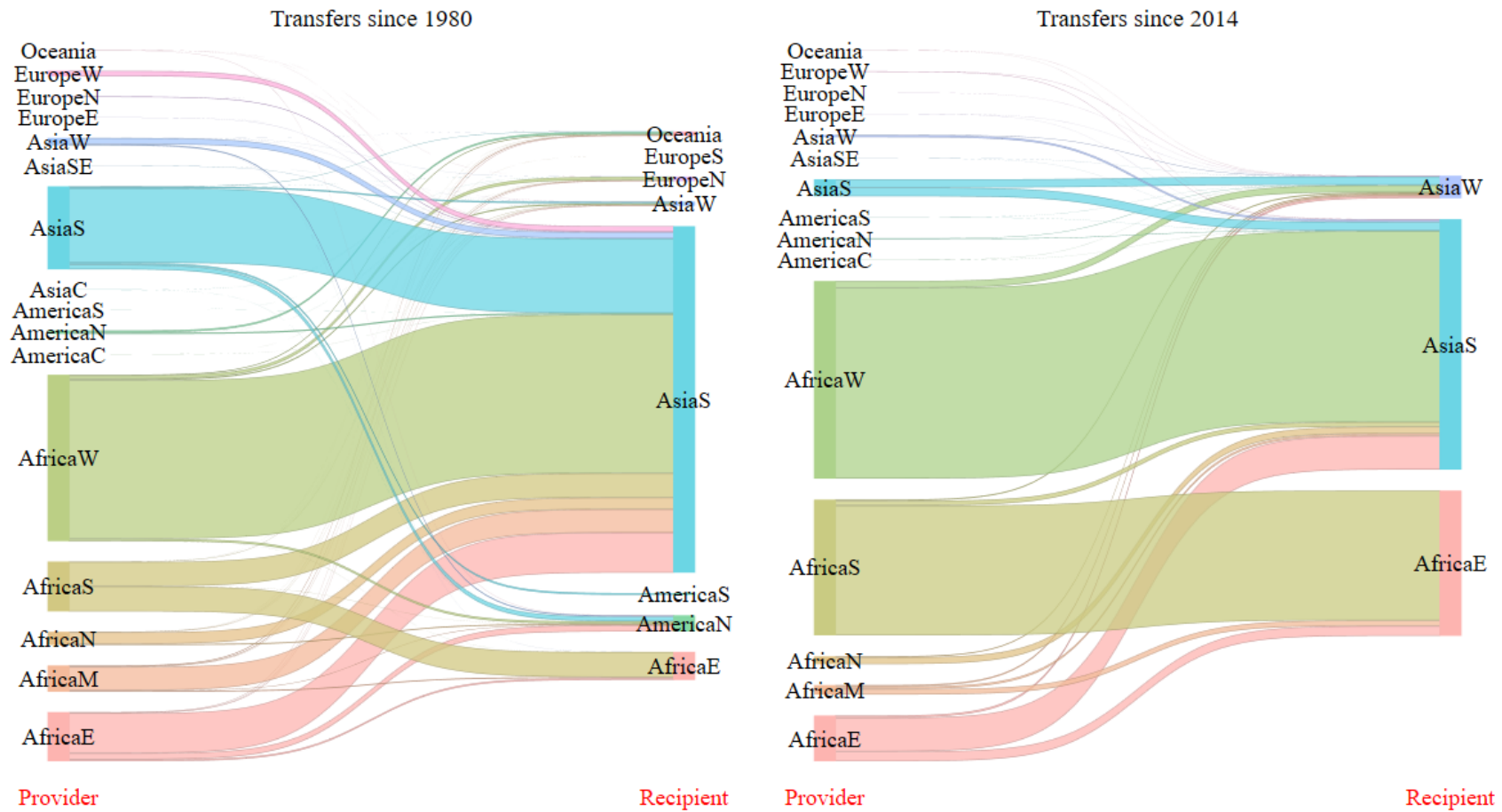
Cowpea:



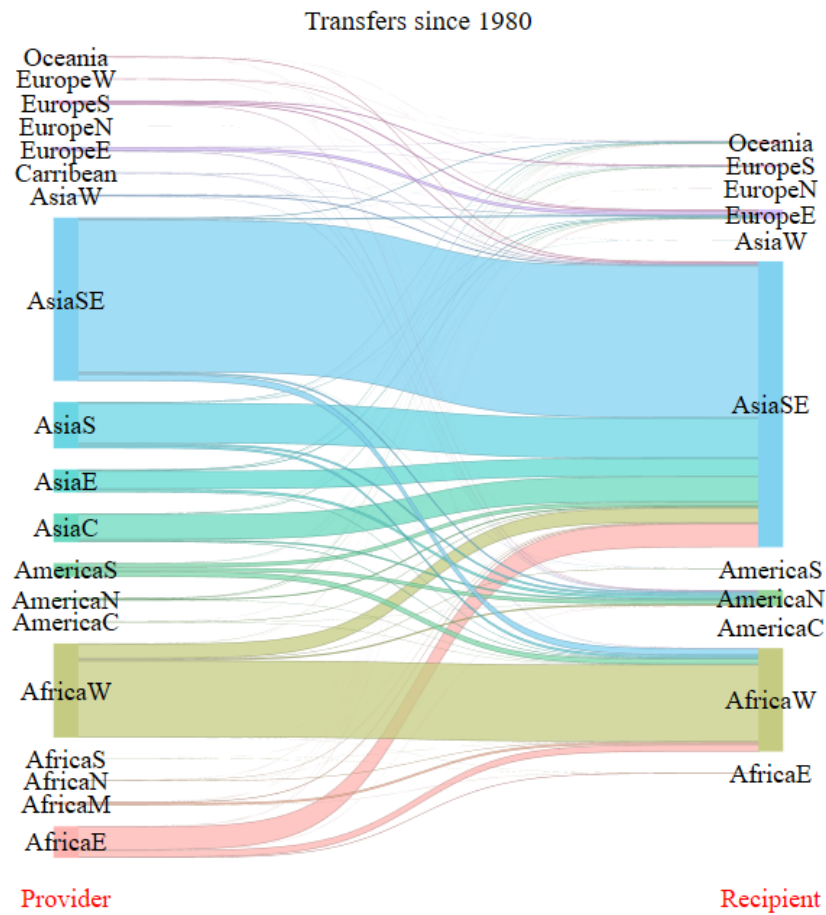
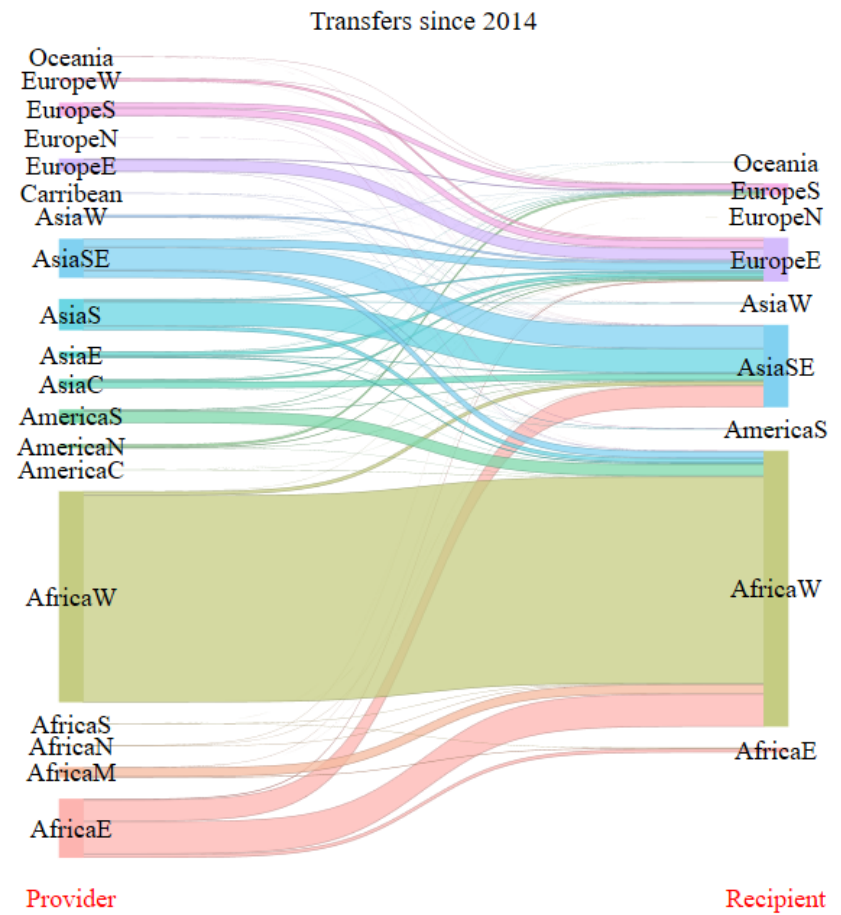
Maize:



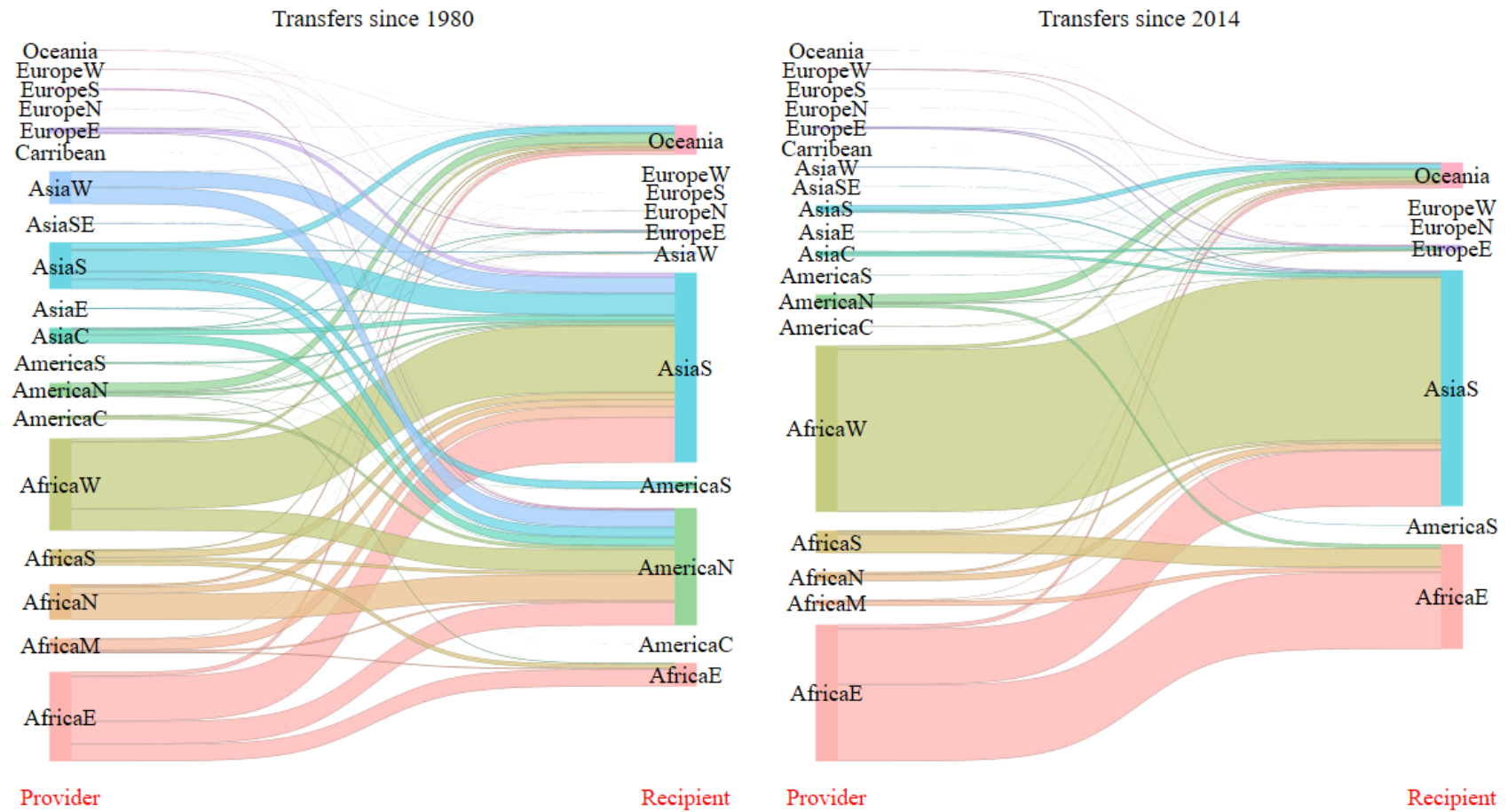
Pearl millet:



Rice:



Sorghum:



Source: Authors' compilations.

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