WHITE PAPER

Achieving global food security without compromising free trade or agricultural productivity: a global perspective on the EU's Green Deal and the role of innovation for sustainable agriculture

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1. INTRODUCTION

Policy decisions arising from the Russian war in Ukraine have put food security at risk (FAO, 2022a). Other military and civil conflicts, the COVID-19 pandemic, and an increase in climate change-related weather events during the past years have likewise highlighted how the availability and accessibility of food, feed, fuel, and fibre can be negatively affected in both quantity and price. Projections of an uncertain macroenvironment over the next ten years (OECD and FAO, 2022) further suggest potentially drastic consequences for hundreds of millions of people in low-income countries, and for the vulnerable populations of developed nations.

Against this backdrop, it is critical to examine the driving role of policy and the potential for unintended consequences. Regulations affecting agricultural production and food trade globally can have negative repercussions when governments do not strike the right balance between environmental protection and food security. Certain unilateral decisions can create trade disruptions, legal disputes and retaliation, affecting sustainable agricultural development and the global economy. Unilaterally imposed sustainability standards are an example. When applied to food imports without considering the requirements of local production, they can serve as non-tariff barriers to trade and represent a misuse of economic power. They may have the unintended effect of undermining the economic and social development of trading partners in the regions of the world most dependent on trade in food and agriculture for livelihoods and development.

A relevant example of potentially trade-distorting European Union (EU) policies is given by the maxi-mum residue levels (MRLs) of pesticides. MRLs – established to ensure food is safe for consumption and to ease trade – are the highest level of a pesticide residue that is legally tolerated in or on food or feed at the time of harvest when the products are applied according to the label instructions. These levels are set based on the "As Low As Reasonably Achievable" principle and consumer health risk assessments are undertaken at these levels, even though a higher residue level might not pose a risk to consumers. Consequently, MRLs may be set at different levels by different countries, depending on the registered pesticide uses. The environmental impact from the use of the pesticide and possible risk mitigation measures are assessed by the competent authority when the product is approved in the country of use: the impact does not need to be reassessed by the country that imports the food or feed.

The EU is now planning to move away from these internationally established principles for setting MRLs. In its Farm to Fork (F2F) Strategy, discussed in more detail below, the European Commission announced that it will consider environmental factors when establishing MRLs[1]. Other examples of such trade distorting policies exist and serve as warnings[2]. Trade-enabling policies, on the other hand, help foster the development of agriculture, a key sector in terms of delivering on the United Nation (UN) Sustainable Development Goals (SDGs) of poverty eradication, zero hunger

1 On 6 July 2022, the EU notified the World Trade Organization (WTO) under Technical Barriers to Trade about draft regulation on lowering MRLs for the active substances in two pesticides, claiming global environmental impact from their use outside the EU (WTO Committee on Technical Barriers to Trade, European Union Notification number 22-5221, dated 06/07/2022). If this draft regulation is implemented, countries exporting to the EU would need to reconsider the use of those substances in crop production, even though they are officially registered and approved as safe to use in their countries. In this way, MRLs might end up being used as a tool to impose the European Commission's pesticide policy on trading partners, influencing crop production patterns in exporting countries. The European Commission's policy direction is in any case clear: a press release from 22 June 2022 states that "Imported food containing measurable residues of prohibited substances [in the EU] should, over time, not be marketed in the EU" (EC, 2022b).

2 Another example of the distorting effect of "local" regulations on productivity, agricultural income of producing countries and international trade is given by the case of Mexico and its ban on genetically modified corn, expected to take effect in 2024. Economic analysis suggests that the move could likely increase the country's own food insecurity through higher food costs, add USD 4.4 billion to its corn import costs, and impose fundamental and costly changes, particularly to U.S. and Canadian farming and grain handling sectors (WPI, 2022). The ban will, for example, potentially force the world's major corn exporters to shift production to meet Mexico's demands and introduce identity preservation activities that are riskier and linked to volatile supply, inelastic demand and fluctuating price premiums. In these ways, Mexico's policy decisions are likely to exacerbate existing supply chain constraints and subject its economy – and those of its trading partners – to additional volatility in grain supply and pricing.

and economic growth and in terms of tackling climate change, protecting natural resources and enhancing biodiversity. Within this context, Europe is a particularly important case study. With its prominent role in agri-food markets, the EU is a global player in food security and its decisions substantially affect international trade, the food policies of other countries and the availability and accessibility of food globally.

With this in mind, it is important to look at the European Green Deal. As agreed by the European Council in December 2019, the Green Deal is a growth strategy meant to transition the European economy to a sustainable model. The overall goal is for the EU to become the first climate-neutral continent by 2050, resulting in a cleaner environment, more affordable energy, smarter transportation, new jobs, and overall better quality of life. Central, more general elements of the Green Deal include climate action, clean energy, sustainable industry, buildings and renovations, sustainable mobility, and eliminating pollution. Promoting research and development and preventing unfair competition from carbon leakage are other goals. The features most closely linked to EU agriculture are the F2F Strategy and the Biodiversity Strategy.

The F2F Strategy aims to address food systems' environmental issues, equity, sustainability, and the health of Europeans. It also focuses on reducing waste and transforming food production, processing, retailing, packaging, and transportation. The Biodiversity Strategy identifies key drivers of biodiversity loss such as changes in land and sea use, overexploitation, climate change, pollution, and invasive alien species. Biodiversity loss and climate change are intrinsically linked, and nature-based solutions will play an essential role in climate change mitigation and adaptation. The two strategies are meant to be complementary and together promote the restoration of forests, soils, and wetlands and the creation of green spaces in cities.

Overall, the EU's Green Deal is the outcome of a lengthy process of redefining European agricultural policy to focus on environmental objectives. If ultimately implemented through EU regulation in a legislative process expected to take several years and involve the interaction of the EU's institutional powers, it will have significant consequences globally. The impact would be more severe if it adds to distortions that already exist in the system.

The Green Deal and related strategies have been adopted and are now being actively supported. The legislative process for further operationalising and implementing them into EU regulations has been initiated, and so it is essential to explore the impacts of two European strategies on other countries and world regions. We must try to understand the repercussions for global food systems and food security.

We look to contribute to this understanding by examining specific elements of the European Green Deal from a food-security perspective and to initiate a conversation about revising the policy agenda. We want to explore how we can achieve environmental and socio-economic sustainability while ensuring that policy decisions benefit both food security and environmental performance. While the European Green Deal covers many domains and incorporates many approaches, we focus on those most relevant to socio-economic issues and environmental aspects. These include changes in agricultural input use, land use changes, mirror clauses in international trade, and innovation as a means of achieving greater economic, social and environmental sustainability of agriculture.

The paper begins with an overview of the emerging global challenges that make this a particularly critical time to examine agricultural and trade policies in terms of their impact on food security. We then give an overview of the objectives of EU agricultural policy, specifically the European Green Deal, and discuss the potential impacts of supply-related interventions embedded in its F2F Strategy and Biodiversity Strategy at the European and global levels[3]. We discuss the need

3 In the absence of specific peer-reviewed assessments, our analysis does not extend to other European Green Deal strategies such as the Chemical Sustainability Strategy. We nonetheless integrate potential negative effects on food security into our forward-looking conclusions.

for a policy framework that is better able to address not only socio-economic and environmental objectives in general, but also food system vulnerability, especially food security, and explore how innovation can support these goals. Our concluding remarks encourage further discussion on how to improve food security while ensuring the economic prosperity of the agricultural sector and providing environmental benefits to society at large.

2. EMERGING GLOBAL CHALLENGES AND FURTHER POLITICAL CONTEXTS

Fundamental market developments

The global population is expected to rise to 9.7 billion people by 2050 from about 7.9 billion currently and could increase to 10.4 billion people by 2100 (UN, 2022). Accompanied by income growth, changing dietary habits, and increasing meat consumption in less developed countries, researchers expect a significant increase in the global demand for food (Alexandratos and Bruinsma, 2012; Tilman et al., 2011) and a change in consumption patterns towards more resource-intensive and perishable food products (FAO, 2021a; b; OECD and FAO, 2022). The results of a recent meta-analysis of 57 studies suggests that under a business-as-usual scenario, total global food consumption will increase by more than 50 percent by 2050 compared to 2010 (van Dijk et al., 2021)[4].

The recent exceptional growth rate in agricultural demand is expected to slow at least in the next decade (OECD and FAO, 2022). Driven by an expected slowdown in demand growth in China and other middle-income countries, and in the global demand for biofuels, OECD and FAO (2022) expect global demand for agricultural commodities (including for non-food uses) to grow at only 1.1 percent annually over the next decade. They project that global food demand will increase by 1.4 percent per year over the next decade, driven by population and per capita income growth. At the same time, they estimate that global agricultural production will grow by 17 percent over the next ten years, but note that simultaneously ending global hunger and putting agriculture on track to contribute to reaching the Paris Agreement reduction in greenhouse gas (GHG) emission would require a more substantial acceleration in productivity growth. Their scenario analysis suggests that simultaneously achieving these targets would require an average global agricultural productivity increase of 28 percent over the next decade.

Additional developments, heightened food insecurity

We are already facing a challenge, and it is critical to remember that these forecasts cannot fully integrate impacts from geopolitical crises, pandemics, major changes to climate conditions or the changing policy environment. Though the details go beyond the scope of this paper, potential additional impacts of some of these events are covered in references including Malico et al. (2019), Nakada et al. (2014), Yadaw et al. (2020), and USDA (2020; 2022). [5]

4 This increase in consumption will affect commodity crops, but also meat, fibre, and dairy. Biofuel production is forecast to increase as well (Muscat et al., 2020; IAE, 2021).

5 It should be noted too that extreme weather events, i.e., consequences of climate change, and conflicts such as the Russian war in Ukraine affect numerous world regions simultaneously. The combination of policy instruments that tend to tighten international markets and poor harvests in multiple regions at the same time makes it more time-consuming and costly for international markets to react. Increased food insecurity in terms of limited availability of food and higher food prices is the potential outcome. For many countries and communities, the current situation already means a lack of access to regular meals. Further down the line, high-income countries, which can pay higher prices and compensate (some) consumers via social policy measures, may deal and adapt. Less developed countries and the poor segment of their populations will suffer the greatest harm.

Indeed, many world leaders have expressed their concern that trade disruptions, record prices and excessive volatility in agricultural and food commodities could jeopardise the food security of all countries, particularly the least developed countries and net food importers, which are disproportionally affected by the crisis (see, e.g., G7 Germany, 2022). The current situation is particularly hard on developing countries for two additional reasons: many now face unusually high debt levels because they increased public spending in response to the COVID-19 pandemic, and many must pay off debts in U.S. dollars USD), which have gradually become stronger against other major currencies since the second half of 2021 (FAO, 2022a; Cousin et al., 2022).

Ultimately, hundreds of millions of people, particularly in low-income countries, are facing existential threats (von Cramon-Taubadel, 2022). Though some price effects might level out in the mid-term (Glauben et al., 2022), the short-term consequences for net-importing countries with low and very low household incomes are drastic (WFP, 2022).

This looming food crisis has prompted a newly awakened awareness that the primary task of agriculture lies in the production of food. Food security, which has been taken for granted in many high-income countries, is on the policy agenda again. Given that policies have international and geopolitical dimensions that go beyond merely country-specific or regional considerations (von Cramon-Taubadel, 2022), we have to ask: does existing policy address these issues?

3. EU POLICY OBJECTIVES AND IMPACT ASSESSMENTS OF THE EUROPEAN GREEN DEAL

This is a critical moment for examining the impact of agricultural policy, particularly regulations that affect agricultural production and food trade. We must ensure that they do not lead to unintended consequence that further threaten food security, either locally or abroad. The European Green Deal, with its F2F Strategy and Biodiversity Strategy, is an example that requires careful examination. [6] The EU is an important market for agri-food (see, e.g., EC, 2022a), and the region's political leaders have expressed an intention to spread their policies through Green Diplomacy [7] and, potentially, trade measures.

European Green Deal

European agricultural policy has undergone constant reform. By the 1980s, the main political goal had gone beyond simply producing sufficient amounts of food and rather targeted a multifunctional European agricultural model meant to be versatile, sustainable, and competitive (Gaupp-Berghausen et al., 2022). EU agricultural policy aims have been constantly adapted and reformulated since. Today, the ten objectives that form the basis for EU agricultural policy development between 2023 and 2027[8] do not explicitly include food

6 It should be noted that although our analysis focuses primarily on the F2F Strategy and Biodiversity Strategy, there are other relevant elements in the European Green Deal that deserve careful evaluation for their joint effects on food security and the viability of farming. These include the Chemical Sustainability Strategy, which in itself could have a major impact on the availability of technical solutions for agriculture. All of these strategies are designed to make the EU economy sustainable and productive, but goals such as reducing chemical inputs will have significant impacts on farmers inside and outside the EU, and the combined effect of the three strategies will ultimately affect the viability of agriculture in environmental, economic, and social terms.

7 This term refers to preventive diplomacy that seeks to build resilience and harmonise the interests of the state with the interests of conservation and sustainable development. In June 2003, the European Council decided to launch an initiative to promote the integration of environmental objectives into external relations (EU Green Diplomacy) and to establish an informal network of officials working on international environmental and sustainable development issues (see, e.g., https://ec.europa.eu/commission/presscorner/detail/en/DOC_03_3 (last access: 5 September 2022))

8 These objectives are: (1) to ensure a fair income for farmers, (2) to increase competitiveness, (3) to improve the position of farmers in the food chain, (4) climate change action, (5) environmental care, (6) to preserve landscapes and biodiversity, (7) to support generational renewal, (8) vibrant rural areas, (9) to protect food and health quality, and (10) to fostering knowledge and innovation (European Parliament and Council of the European Union, 2021).

availability and security. Both have been taken for granted in the EU since the late 1980s (Gaupp-Berghausen et al., 2022).

The European Green Deal, per EC (2019), introduces an additional narrative because it "… *aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use. It also aims to protect, conserve, and enhance the EU's natural capital, and protect the health and well-being of citizens from environment-related risks and impacts*."

Though the European Green Deal covers all sectors, agriculture plays a key role and the F2F Strategy (EC, 2020a) and the Biodiversity Strategy (EC, 2020b), as discussed above, form the core of the relevant policy. Objectives of the two strategies that are linked to ensuring the sustainable consumption of food and other agricultural commodities are generally formulated in qualitative terms. Many of those focused on sustainable production have quantitative target values. For example, by 2030, the agricultural sector should:

- contribute to a reduction of at least 55 percent in net greenhouse gas (GHG) emissions,
- reduce the nutrient loss by 50 percent and the use of chemical fertilisers by 20 percent,
- reduce the use and the risk of chemical pesticides by 50 percent,
- decrease sales of antimicrobials by 50 percent,
- increase the area under organic farming to 25 percent of all used agricultural area, and
- establish a minimum of 10 percent non-productive area.

Assessing the impact of the two strategies

Integrating and implementing the two strategies into European regulation will take several years and involve the interaction of the EU's institutional powers. Quantifying their potential impacts is at the same time a challenge because of the need for refinement in legal provisions to ensure balanced operationalisation and implementation. Six initial impact assessments are nonetheless available.

These assessments, generally based on standard calculations of agricultural economics and modelling approaches, are, in alphabetical order: Barreiro-Hurle et al. (2021), Beckmann et al. (2020), Bremmer et al. (2022), Henning et al. (2021), Kühl et al. (2021), and Noleppa and Cartsburg (2021). While each study covers only selected strategic aims, overall, they offer valuable insight. It should be noted that these studies generally focus on the implementation of the two strategies in the EU alone.[9] Though the focus of this paper is on the potential impact outside the EU, it is nonetheless necessary to examine possible internal effects first.

Existing literature focused on economic impacts within the EU

We have drawn partially on Wesseler's (2022) meta-analysis of the six impact assessments to give a summary in the following. We note, however, that this meta-analysis and further discussion based on these studies are still limited because they only address quantifiable supply-side objectives of the two strategies: unquantified demand-side objectives (see EC, 2020 a; b) are not included because they do not lend themselves to concrete calculations. They are nevertheless clearly relevant to impact assessment (see, e.g., Purnhagen, 2022). As such, the studies are incomplete and do not provide a holistic picture of the potential outcomes. The studies also address different objectives and use varying economic models and calculations and so cannot be compared directly; analyses lead to different results. The table below outlines the coverage and gives selected results of the six studies.

9 The analysis of Beckmann et al. (2020) additionally includes scenarios focused on implementation of the two strategies beyond the EU, and on a global scale. To meaningfully compare the outcome of the six impact assessments, we have excluded the specific findings associated with these broader scenarios.

Coverage and selected results of ex-ante studies on the impacts of the European Green Deal

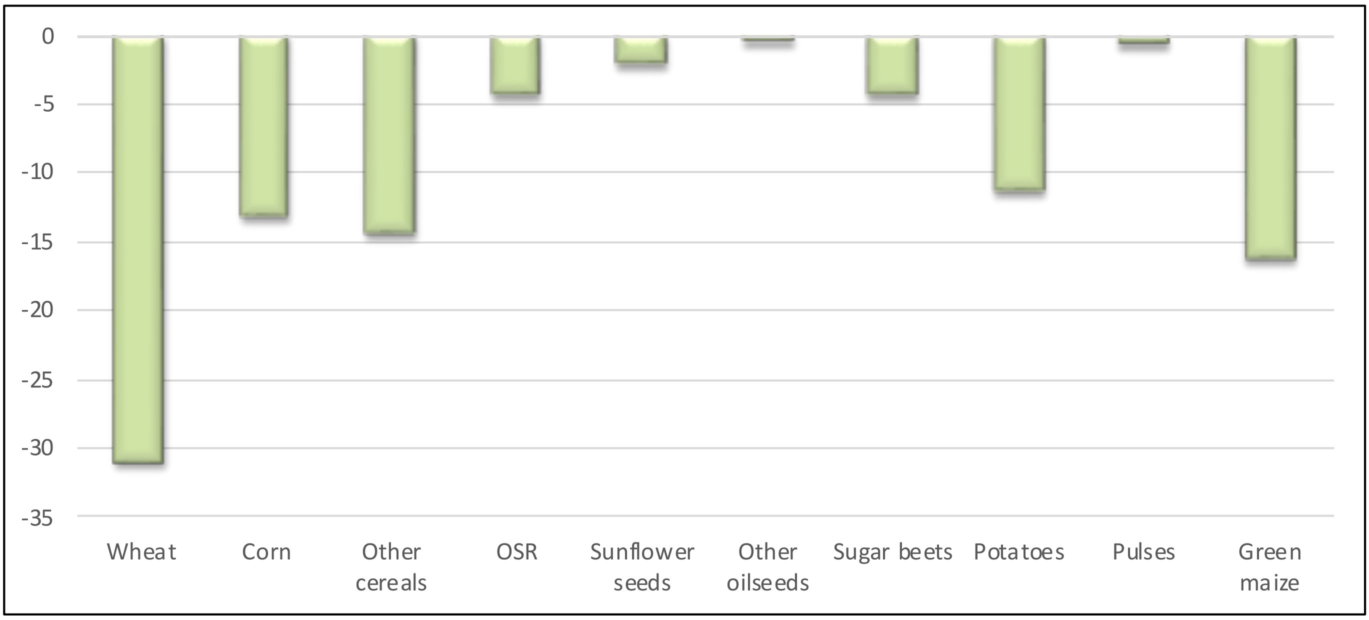
	Barreiro-Hurle et al. (2021)	Beckmann et al. (2020)	Bremmer et al. (2022)	Henning (2021)	Kühl et al. (2021)	Noleppa & Cartsburg (2021)
Covered objectives						
Nutrient loss: –50 %	X		X		X	
Fertiliser use: –20 %		X	X	X	X	X
Use of pesticides: –50 %	X	X	X	X	X	X
Risk of pesticides: –50 %	X	X	X	X	X	X
Antimicrobials: –50 %		X				
Organic farming: 25 %	X		X	X	X	X
Non-productive area: 10 %		X				X
Assessed impacts (production and price impacts in %)						
Production of cereals	–15	–49	–16	–24	–14	–26
Production of oilseeds	–14	–61	–18	–20	–14	–24
Production of other crops	up to –12	–5	up to –31	up to –32		up to –24
Production of animal produce	up to –13	up to –14		up to –20		
Price increases at farm level	10 on average	17 on average	up to 41	up to 58		between 3 and 14
Agricultural trade	Decrease in net export	More imports fewer export	Increase in net import	More imports fewer exports		More imports fewer exports
Sectoral and/or societal costs	up to EUR 18 billion	up to USD 71 billion	up to EUR 12 billion			up to EUR 29 billion

Source: Own table, partly based on Wesseler (2022).

Despite the limitations of our approach, the magnitude of the potential impact is clear from the analysis and this allows for unambiguous conclusions. Findings, which cover the entire EU and link to its trading partners, can be summarised as follows (for more details, see Wesseler, 2022):

- **Decline in production:** Achieving the defined objectives would lead to a reduction in agricultural crop and livestock production in the EU. A decline in production of 24 percent for cereals and of 25 percent for oilseeds could be expected on average. This would also shrink the domestic food supply.
- **Higher prices:** This reduction would be accompanied by higher prices for agricultural raw mate-rials and food. An increase in commodity prices of no less than ten percent should be expected.
- **Decline in agricultural and economic growth:** Shrinking production, higher prices for consumers, and a deteriorating trade situation will all affect sectoral and economic prosperity. Unless bolstered by additional government transfers, agricultural sector income and the societal income generated, e.g., by input suppliers and output processors along the value chains, would shrink considerably. Indeed, the values in billions of EUR above should be considered low because additional administrative, information, and communication costs associated with the policy changes have not been meaningfully considered (Wesseler, 2022).
- **Decrease in exports:** Enforcement of the two strategies would lead to a decrease in EU exports of some key agricultural produce, while imports of other key commodities would increase accordingly. The EU´s net trade position would thus potentially deteriorate, and it could even be-come a net importer in some markets where it is a net exporter. The share of food coming from abroad will increase at the expense of domestically grown food. The authors are in agreement on this point. The trade balance with respect to all major arable crops would be negatively affected, and millions of tons of cereals, oilseeds, and other crops would be missing in the EU if the two strategies are fully implemented (Noleppa and Cartsburg, 2021). This is illustrated in the figure below.

Trade balance effects of the EU's Farm to Fork strategy and Biodiversity strategy (in million tons)



Source: Own figure based on Noleppa and Cartsburg (2021).

Non-economic consequences in the EU

Apart from these economic consequences, some of the impact assessments and other studies address potential environmental, broader sectoral and societal impacts, which are more difficult to quantify. Though many look likely to affect third countries primarily and are discussed further below, some are more specifically relevant to the EU. Research predicts:

- **More expensive land:** Land already used for agriculture – especially in the EU – would become more expensive. To further satisfy markets, entrepreneurial European farmers will look for more land, which is already a very scarce resource in the EU. Barreiro-Hurle et al. (2021) and Henning et al. (2021) model regional land price increases of up to 200 percent.
- **Reduction of yield:** The rationale behind this is that enforcing the two strategies – in particular, allocating a substantial amount of land to organic farming and reducing pesticides and fertilisers – would tend to reduce yields (Wesseler, 2022). A significant decline in farm income, will also affect farmers' ability to invest in nature-positive solutions, making the sector increasingly less receptive to innovation and negating opportunities for sustainable increase in productivity.
- **Legal challenges:** Finally, Pelkmans (2021) and Purnhagen (2022) also see challenges from a legal perspective. According to the authors, international trade regulations and other constitutional issues need to be addressed and corresponding problems resolved before the two strategies can be enforced.

These impact assessments show that enforcing the supply-side targets of the European Green Deal's two strategies may have certain negative socio-economic and environmental consequences. Although the assessments are based on simplified models (see Wesseler, 2022), the results show a clear trend and point in a similar direction: we can expect shrinking EU production and higher world market prices. This will negatively affect global agricultural trade and food security.

Implications for international agriculture and food trading relationships

While the studies focused on the EU, they nevertheless identified areas where the policies may have a significant impact abroad: notably trade, but also environmental issues linked to land use change that will likely affect food security. All of these topics merit careful examination. When the European Green Deal goes ahead, changes in international agricultural trade will particularly affect food security, especially at the global scale as the EU is one of, if not the most, food-secure regions in the world (Beltran et al., 2021; Paarlberg, 2022). We therefore agree with Tolu (2022): implications for international agriculture and food trading relationships are critically important.

Available impact studies focus on the EU and no meaningful scenario or modelling approaches have been used to examine where changes in crop production and consumption will occur globally. It is therefore difficult to say how specific agricultural trade flows between partners might be affected. Some relevant observations and opinions from academic experts are nonetheless available.

Faichuk et al. (2022), for instance, argue that most researchers studying the impacts of the new policies on international trade point to the threat of a slowdown in agri-food trade with the EU. Tolu (2022) finds that an EU adoption of higher production standards would inevitably affect global net ex-porters. Schiavo et al. (2022) support this, arguing that an implementation of the two strategies would lead EU farmers and processors to be crushed by international competitors and put world food security at risk. This is because food security and trade go hand-in-hand (Hackenesch et al., 2021) and any distortion in the former ultimately leads to distortions in the latter.

Implementing the two strategies may therefore affect international agricultural trade and, consequently, non-EU food markets both through direct market price and quantity changes, and indirectly through changing market standards.

Direct market price and quantity changes leading to food insecurity

The six impact assessments of the European Green Deal indicate a substantial price increase primarily at the global level, though also at the EU level. This finding is also supported, though usually not in quantitative terms, by other scientists and experts:

- According to Baquedano et al. (2022), policies that restrict the use of agricultural inputs have been shown to increase international food prices and heighten global food insecurity.
- Faichuk et al. (2022) argue that a decline in exports from the EU and a general reduction in trade activities resulting from implementation of the European Green Deal would lead to in-creasing food prices and costs at the global scale. This would have an added negative impact on food security.
- Because the EU is a major player in the agricultural and food trade (Faichuk et al., 2022), the envisaged input reduction in the EU could lead to a substantial decline in the global food supply and a considerable increase in international food prices, according to Beckman et al. (2021). Having less available food places more pressure on distribution and trade.
- Domestic supply and demand changes linked to the two strategies would, according to Dekeyser and Woolfrey (2021), further contribute to world market shortages and therefore to higher international food prices. This would increase global food insecurity.

Scientists also see a direct relationship between international food price increases and global food security. The higher the prices, the higher the food insecurity. Developing nations, particularly many African countries, which have fast-growing populations who mostly live in urban areas and see changing dietary patterns, and increasing reliance on food imports, are likely to be most affected (Dekeyser and Woolfrey, 2021).

Overall impact on global food insecurity

We can measure the impact of such international trade and market distortions on global food security. The economic rationale is simple: as consumers worldwide pay a greater share of their income for food, relative incomes decline (Beckman et al., 2021). This will leave some behind due to the following reasons:

- **Price increases:** Various impact assessments indicate an average price increase of between ten percent and 17 percent, and sometimes more. Quoting the World Bank, Bruce-Lockhart and Terazono (2022) argue that for every 1.0 percentage point increase in global food prices, we can expect an additional ten million people to fall into extreme poverty and subsequently face heightened food insecurity. Beltran et al. (2021) argue that a 1.0 percentage point increase in food prices should be associated with more than 20 million additional undernourished people at the global scale. In the end, estimates suggest that anywhere from 100 million to more than 300 million people might be significantly affected if the two strategies are enforced.
- **Food insecurity:** Baquedano et al. (2022) calculate that between 30 million and 170 million more food-insecure people, all in developing countries, would result from an implementation of the two strategies. Beltran et al. (2021) estimate 20 million to 180 million additional food-insecure people in more than 70 low- and middle-income countries. Noleppa and Cartsburg (2021) argue that food availability would shrink for 130 million to 190 million people due to the supply-side effects of the two strategies.

Let's put those numbers into perspective: according to Bruce-Lockhart and Terazono (2022), who quote the FAO, the Russian war on Ukraine can be linked to 13 million to 17 million more undernourished people. The impact of the European Green Deal might therefore be ten times greater than the food insecurity impact that we now face, and which is already leading to remarkable agricultural policy adjustments.

It is therefore clear that the two strategies of the European Green Deal, if not properly managed, have the potential to substantially change the geopolitical situation through market and trade distortions that create new challenges for states and societies (Wrzaszcz and Prandecki, 2020).

Negative environmental externalities

The two strategies may also have unintended consequences for the environment and sustainability. Following implementation, the EU's additional net imports could come principally from regions with lower environmental standards, particularly in terms of GHG emissions (Schiavo et al., 2021). Subsequently, lower European production will lead to increasing agricultural production outside Europe. Depending on where it takes place, this shift could generate negative environmental externalities (Dekeyser and Woolfrey, 2021).

According to Beckman et al. (2020), decreased agricultural production in the EU and the associated increase in global food prices are likely to intensify agricultural production in Africa, Asia and Latin America primarily. These regions generally have lower environmental standards and less sustainable agricultural practices (as defined by EU standards) than the EU and so this geographical shift in production could undermine many of the environmental benefits attributed to the two strategies (Barreiro-Hurle et al., 2021; Dekeyser and Woolfrey, 2021).

A simple comparison illustrates this effect: according to FAO (2022b), the GHG emission intensity per unit of cereals produced is 19 percent higher globally than in Europe. This is largely linked to the energy embedded in agricultural inputs, particularly fertiliser. Since the specific factor intensity per kilogram of output is rather high in the major competitors to the EU in agricultural trade, the net balance of a production shift to these other countries must be negative. This particularly applies to Brazil, the USA, Norway, and China – four of the top five leading agri-food exporters to the EU (Faichuk et al., 2022).

Indirect land use change, GHG emissions and biodiversity loss

Environmental leakage would mostly be driven by the need for additional land due to yield differences between Europe and the rest of the world: more land must be farmed to produce the same amount of food, making the environmental problem worse at the global level (Paarlberg, 2022; Clark 2020).

Pursuing land expansion rather than agricultural intensification is the greatest threat to global biodiversity and substantially affects climate change (IPCC, 2019). This dynamic is projected to strengthen and have a particular impact on countries in Sub-Saharan Africa and Latin America (Williams at al., 2021), as well as in South-East Asia. This is a particularly important detail because biodiversity is not equally distributed across the globe. There is more richness of species and biomass per unit of land in the areas around the equator - those areas identified as most likely subject to increased pressure on land expansion - and less in temperate zones such as most of the EU (Saupe et al., 2019). It is important to note too that over centuries this has led to more carbon sequestration below- and/or above-ground in still available natural or semi-natural habitats at lower latitudes.

Impact assessments show that the two strategies would lead to indirect land use changes (ILUC), the conversion of natural or semi-natural habitats into agricultural land. Excluding the ten percent of EU agricultural area meant to be non-productive and set aside for nature and semi-natural habitats, Bremmer et al. (2022) link ILUC of 4.4 million ha and Henning et al. (2021) of 7.1 million ha to the implementation of specific F2F Strategy scenarios. Including an additional set-aside of ten percent driven by the Biodiversity Strategy, and taking into account the fact that it is necessary to increase the amount of land used for growing legumes to meet the nutritional needs of crops (Connor, 2018), particularly in terms of nitrogen,[10] would further increase the ILUC caused by supply-side effects to well above ten million ha according to Noleppa and Cartsburg (2021). This cannot be effective in terms of mitigating climate change and preserving biodiversity (Paarlberg, 2022), especially since it should be noted that a ban of any pesticide in so-called sensitive areas as proposed by the European Commission in the Sustainable Use Regulation could mean that the loss of agricultural area is even higher than outlined in the F2F Strategy.

Research from the European Union Intellectual Property Office and the Community Plant Variety Office, mainly based on Noleppa and Cartsburg (2021), have recently calculated the amount of additional GHG emitted at the global scale and the worldwide biodiversity loss that can be associated with ILUC (EUIPO and CPVO, 2022):

- **Increased GHG emissions:** Approximately 200 million additional tons of carbon dioxide are emitted to the atmosphere per one million ha of ILUC. The global ILUC potentially caused by the European Green Deal could therefore easily result in the emission of 2.0 billion tons of carbon dioxide. This is a volume almost equivalent to the annual emissions of a country like Russia (World Bank, 2022).
- **Accelerated biodiversity loss:** Per one million ha of ILUC at global scale, it could be as large as the richness of species that can now be found in 0.35 to 0.55 million ha of Brazilian or Indonesian rainforest. Implementing the two strategies in the EU could therefore result in a loss of global biodiversity comparable to the biodiversity now found in 3.5 to 5.5 million ha of, for in-stance, precious rainforest.

The biodiversity loss seen globally could therefore far outweigh any gains in the EU (Williams et al, 2021). EU member states may therefore outsource environmental damage to other countries while potentially taking the credit for green policies at home (Fuchs et al., 2020). While the EU believes that its two strategies are "green" in the absence of major domestic demand changes, this may not be the case. Converting land to agricultural production would damage wildlife habitats and the climate (Paarlberg, 2022).

This potential for externalizing environmental damage is considered one of the main risks of the agri-cultural strategies supported by the European Green Deal (Beltran et al., 2021). According to the authors, the EU already acknowledges the risk of these embedded externalities and recognises that a change in the EU's domestic agricultural and food system should be accompanied by policies that help raise standards globally. In other words, the EU wants to tackle the problem of outsourcing environmental degradation (Beltran et al., 2021) by exporting its standards. Policy measures meant to encourage exporting countries to re-evaluate their environmental standards are therefore currently being discussed (Matthews, 2022a).

Accelerating a global transition to sustainable food production

The EU intends to take a leadership role in accelerating a global transition to what it considers sustainable food production (Leonard et al., 2021; Teevan et al., 2021). In EC (2020a), we read "Through its external policies, including international cooperation and trade policy, the EU will pursue the development of Green Alliances on sustainable food systems with all its partners in bilateral, regional and multilateral fora […] Appropriate EU policies, including trade policy will be used to support and be part of the EU's ecological transition. The EU will seek to ensure that there is an ambitious sustainability chapter in all EU bilateral trade agreements. It will ensure full

10 It is important to note that this is often neglected in modelling approaches (Beltran et al., 2021).

implementation and enforcement of the trade and sustainable development provisions in all trade agreements […]" (see also Paarlberg, 2022). What does this mean? According to Fuchs et al. (2020), the EU wants to show the rest of the world how to be sustainable and competitive. Reducing the environmental footprint of agricultural production is a worthy and necessary objective (Paarlberg, 2022). Since the EU tends to have high, if not the highest, regulatory standards globally, especially in terms of the environment (Teevan et al., 2021), most of their current agri-food imports come from countries with environmental laws that are less strict (Fuchs et al., 2020). Aiming to set new global sustainability standards in the agricultural sector and stimulating other countries to follow (Hackenesch et al., 2021) is therefore a good idea in itself. It could, however, turn out to be a complex endeavour with unintended side effects. It is worth considering too that the strictest regulation does not equal the safest or most effective.

Here, it is worth noting that Japan's Ministry of Agriculture, Forestry and Fisheries launched a strategy for sustainable food systems last year (MAFF, 2021). It includes proposals for reductions in the use of chemical pesticides and fertilisers by 2050 as well as an increase in organic farming and sustainable sourcing for import materials. This "Japanese Green Deal" is, however, voluntary and based on a multi-lateral dialogue. It does not have prescriptive elements, and it does not impose production standards on trading partners. It rather strengthens stakeholder engagement at every stage of the food supply chain and promotes innovation to reduce environmental pressures. According to the strategy, there is no "one-size-fits-all" solution that leads to sustainable food systems. Each country has its own priorities and must find solutions that take into account geography, climate, agriculture, and other relevant conditions. The Japanese approach also offers support in terms of innovation: technologies developed in Japan (e.g., digital tools and pesticides) can help countries facing similar challenges. In these ways, the "Japanese Green Deal" is a tool to promote trade-offs and encourage dialogue among stakeholders.

We do not yet know what policy instruments the EU will choose to pursue. While effective multilateral agreements are the gold standard, they are usually less ambitious than bilateral or unilateral policies and often lack effective means of enforcement (Matthews, 2022b). What is clear is that under the EU's two strategies, those who wish to export agricultural and food products to the EU might become subject to the same or at least similar restrictions and limitations as those EU farmers will have to face in future. Teevan et al. (2021) argue that the EU will try to use its regulatory power to support a global green transition through a "Brussels effect," that is, a process of regulatory globalisation causing a de facto externalization of its standards through market mechanisms.

Projections show that requiring imported food to comply with EU regulations and standards can be-come very costly for many trading partners[11] (see, also, Teevan et al., 2021). Developing countries that do not have the resources to upgrade relevant production systems quickly enough face particular challenges (Lopes, 2021).

Restricted access to European markets –opinion of academic experts [12]

Already today, many developing countries in Africa and elsewhere face restrictions in terms of accessing European markets. Hurdles include non-tariff barriers as well as regulations and standards for particular products (Hackenesch et al., 2021). Even tougher EU regulations

11 Beckman et al. (2020) explicitly addressed this issue by examining economic implications of the European Green Deal pro-posal beyond the EU, performing a range of policy simulations on several proposed targets using broader adoption scenarios. They found that adoption of the two strategies worldwide could increase food prices by up to 89 percent. This would negatively affect consumer budgets and ultimately reduce worldwide societal welfare by as much as USD 1.1 trillion. The authors went on to estimate that these higher food prices could increase the number of food-insecure people in the world's most vulnerable regions by as much as 185 million. In this case, food insecurity is spread across all regions, though Africa and other Asia are the most impacted regions because they could experience the largest increase in commodity prices and the greatest GDP declines.

12 The following input and in particular the lack of local assessments was also addressed through surveys carried out by an external journalist with academic experts having specialised knowledge of different regions. The experts are Marcelo Henrique Aguiar de Freitas; Wandile Sihlobo; Tinashe Kapuya; Henri Rueff; Philipp Aerni.

and standards would further tighten market access for developing countries if they are not counterbalanced by assistance with local development of relevant science and technology, institutions, management, and absorptive capacity of producers (Hackenesch et al, 2021).
We must also consider associated socio-economic impacts, which include international agricultural trade impacts (Hackenesch et al., 2021), because further trade distortions could accelerate the emerging global food security crisis. Sihlobo and Kapuya (2021) argue that overly demanding standards could leave smallholder farmers out of some of the most remunerative sustainable agri-food systems because they can seldom afford the high costs of adopting new regulations and certification without financial support. According to Kirsch (2020), the introduction of such standards could cut EU agricultural and food imports in half because the relevant exporters are unable or unwilling to apply the new environmental standards (see also Faichuk et al., 2022). Indeed, countries with less developed sustainability models may target other markets, at least in the short to medium term (Sihlobo and Kapuya, 2021). Even countries with rather solid agricultural sustainability models such as Brazil have difficulty following criteria that do not consider local growing conditions. When considering agricultural production, the characteristics of local production, such as the number of harvests per year, the use of fertilisers, region-specific pests and diseases, temperature and growing conditions, etc., must be taken into account.

Legal aspects and potential dispute

The EU is also likely to meet strong resistance if it promotes its own standards at the global level. Asking farmers to stop using some valuable inputs that increase land productivity will be a "no go," particularly in countries with unmet food needs. This would further limit farm production and income and push food prices for the poor in urban centres even higher (Paarlberg, 2022). Long-lasting dispute settlements affecting the free movement of tradable commodities could result (see, e.g., Matthews, 2022b).

Some exporting partners may consider the EU's measures to be illegal, protectionist, or challengeable under the WTO dispute settlement system. They may prefer that each situation be analysed case-by-case, with technical, scientific, and economic criteria taken into account. Paarlberg (2022) explicitly argues that using trade regulations such as mirror clauses, discussed in the box below, to pursue the two strategies abroad and promote the adoption of European-style measures will remove significant options, especially for poorer countries. For this reason, the author finds that the EU must consider the consequences of its domestic decisions abroad. We also believe that this is essential to avoid further trade disruptions and the associated potential increase of food insecurity. The challenge is to ensure that whatever path is chosen is not used as a way of creating added difficulties for trading relationships (Tolu, 2022).

Mirror Clauses

Mirror clauses are reciprocal standards for European products and those imported from third countries (French Government, 2022). As such, they aim to subject imports to EU production requirements in a way that is compatible with WTO rules (Matthews, 2022b). The impact of mirror clauses on agricultural and food products can only be discussed on a theoretical level for now because none have yet been put into practice. The only relevant mirror clause so far, addressing the use of antibiotics in live-stock management, has entered into force, but key acts setting out practical enforcement are still outstanding (Matthews, 2022b).

Sound impact analysis requires the specifics of a given clause and details on how it is to be implemented. Some arguments pointing to a link between mirror clauses and difficulties in terms of trade and food security nevertheless exist. Most importantly, mirror clauses introduced uniquely to protect production in the EU would be inconsistent with WTO rules (Matthews, 2022b). Instead of only requiring third country producers to meet comparably high EU standards, the EU must also allow its pro-ducers to export when meeting often lower foreign standards. Since this seems unlikely, it would be the foreign supplier who must bear the costs via domestically increasing expenses in production, processing and logistics.

Any EU attempt to introduce mirror clauses, for instance in the case of import tolerances with respect to certain pesticides, must be carefully assessed in terms of benefits and risks, as well as feasibility. Mirror clauses now being discussed, e.g., with respect to MRLs of pesticides, do not seem to be enforceable by trading partners. They must therefore be considered bans on the import of agricultural commodities; moreover, they will most likely cause severe disruptions to international agricultural trade (Matthews, 2022a) and disproportionally harm farmers in developing and other countries (Rid-ley, 2019).

In summary, the legal design as well as the intended and unintended consequences of such clauses must be weighed carefully to avoid discriminating against developing countries through the imposi-tion of practical barriers.

It may be possible to reconfigure trade dependencies, perhaps to have a greater focus on more regional supply chains, if EU standards become mandatory for all trading partners. In this case, diversifying import and export sources might be a new strategy for many countries. Such a new trading system would certainly be less efficient than the current one, which is designed to deliver food commodities at affordable prices. Additional costs will occur, and food prices could become even higher (Bruce-Lockhart and Terazono, 2022).

This is especially noteworthy because the EU has recently committed to improving global food security. It has confirmed that trade, along with domestic production, plays a vital role in improving global food security in all its dimensions. This underscores the need for flow in the agri-food trade and reaffirms the importance of avoiding export prohibitions or restrictions, as is consistent with relevant WTO provisions (WTO, 2022). The EU and other G7 members have also committed to sustainably in-creasing the availability of agricultural products and to avoiding unjustified restrictive trade measures that increase market volatility (G7 Germany, 2022).

Overall, we see that European Green Deal and subsequent policy measures have the potential to significantly affect external countries and global food security. It is critical to avoid negative impacts, especially for countries faced that may struggle in their progress towards the UN 2030 SDGs.

4. THE NEED FOR ENHANCED AGRICULTURAL POLICY AND THE ROLE OF INNOVATION IN MEETING POLICY OBJECTIVES

Several factors have already or will soon converge to further disrupt global agricultural and food markets. They have one common consequence: increasing commodity prices. While wealthy nations may be able to cope with the associated challenges to a certain extent,[13] poorer countries may not be able to access food at reasonable prices.[14] This development usually goes hand in hand with higher market volatility and, thus, uncertainty. While the broad environmental, social and sustainability ambitions of the EU Green Deal can be applauded, such food security concerns are not sufficiently reflected in the current proposal.

Addressing trade-offs

Upscaling the global food system to feed the growing global population both now and until 2050 and beyond, is an overarching concern. Doing so under business-as-usual scenarios, with pressure on the natural resource base and the environmental impacts of increasing production and satisfying food consumption patterns, will diminish the international community's chances of achieving environmental goals. The effects of the Russian war in Ukraine have increased awareness that assuring food security is the basic function of agriculture, but have also raised questions of compromise.

Agricultural policy will always have to deal with trade-offs (see also Kanter et al., 2022) because they are inherent to its nature. We therefore argue that the overall aim of agricultural policy must be to minimise trade-offs between various objectives and maximise goal-specific synergies. How

13 These countries might be able to take, for instance, social policy measures to ensure the access to food for all citizens (von Cramon-Taubadel, 2022).

14 According to FAO et al. (2021), more than three billion people lack access to nutritional diets, and nearly 700 million of them suffer from hunger. Since 2014, the number of severely food insecure people has risen by more than 300 million, or 50 percent. The number of moderately food insecure people increased globally by approximately 400 million or al-most 40 percent between 2014 and 2020 (FAO et al., 2021). Even though Europe is ranked as the global leader in food affordability and the second-best region in the world in terms of food availability in 2020, according to the Global Food Security Index 2020, the region's overall food security has marginally declined since 2021, even before the Russian war in Ukraine disrupted markets and led to price increases (The Economist Intelligence Unit, 2021).

can this be done? We believe that we must question all policy measures and private actions that (1) unnecessarily decrease the supply of agricultural commodities and (2) unreasonably increase the demand for food, feed, fuel, and fibre. We must also address technologies and innovation that focus on increasing the food supply and, ultimately, explore demand-side targets such as dietary change, food waste and loss, and bioenergy policies.

Increasing the food supply while addressing environmental issues

Current and future growth in agricultural production can largely be achieved by expanding agricultural land and/or using more resources and inputs such as pesticides, fertilisers and agricultural machinery. It is also possible to develop and use better inputs thanks to technological innovations or even to apply inputs in new or more efficient ways. We need to know which is the better approach.[15] What is currently contributing most and what can be expected to contribute most in the future?

We can answer this question using Total Factor Productivity (TFP) analysis. The approach distinguishes output growth coming from increased inputs, that is, quantity, from output growth due to improved inputs, or quality (i.e., innovations), in terms of TFP. According to Bureau and Anton (2022), what re-mains as TFP growth can be attributed to a mix of technological progress, that is, the use of novel technologies, and technical efficiency, which is the better use of available technologies. Together, they are also known as innovation (Noleppa and Cartsburg, 2021; EUIPO and CPVO, 2022).

The table below shows changes in, but not levels of, global and regional agricultural output, input, and TFP growth since 1961, also reflecting that many low-income countries, and lower-middle-income countries in particular, still suffer from low use of specific intermediate inputs such as pesticides and fertilisers (see, e.g., Roser, 2019) despite comparably high input growth rates in the past.

Global agricultural output, input and TFP growth changes between 1961 and 2020, by region (in percent)

Growth of …	Global average	Low-income countries	Lower-middle-income countries	Upper-middle-income countries	High-income countries
… TFP	175	135	190	235	195
… Input	215	315	280	245	95
… Output	375	425	530	575	185

Source: Own table, based on USDA (2021).

15 We acknowledge that approaches such as best management farming practices can also contribute to increased productivity, while waste reduction and dietary change can reduce pressure on agriculture. These topics are beyond the scope of the discussion in this paper.

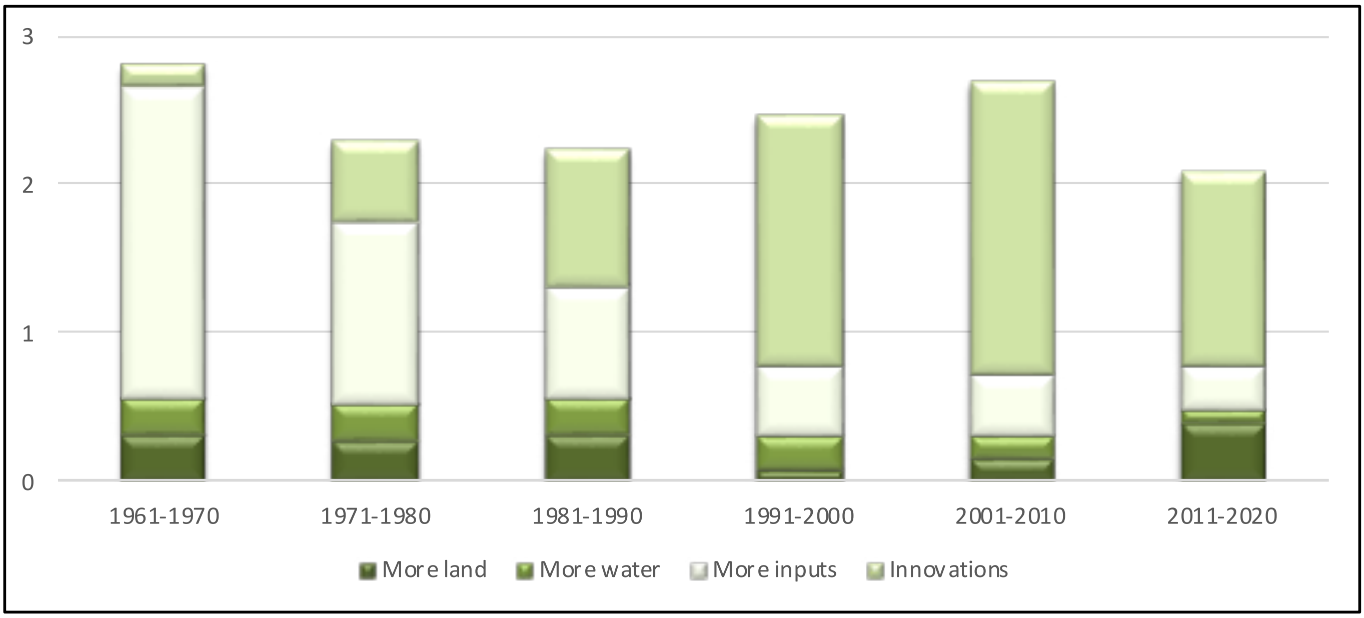
While agricultural output increased considerably, most of it came from increased inputs – that is, greater use of scarce global resources and increased intensification – rather than innovation: the use of inputs increased by around 215 percent in the past six decades, the TFP grew by only about 175 percent.

Examining the table by world region additionally reveals that the importance of input growth (intensification) for agricultural development is lower and that of TFP growth (innovation) higher the more developed the region: in high-income countries, agricultural growth primarily results from innovation.

It is also noteworthy that over time, the sum of yield-determining components such as intermediate inputs and innovations has gained increasing importance compared to increased land use. This has enabled global food and agricultural production systems to maintain output growth of more than 2.0 percent in the past six decades (USDA, 2021). The past decade has seen three rather disadvantageous developments at the global scale, however, as illustrated by the pillars 2001-2010 and 2011-2020 in the figure below:

- Global output growth shrank by approximately 0.5 percent per year to around 2.0 percent per annum.
- This is to a large extent the result of decreasing TFP growth rates: it is much more challenging to generate innovations within the context of restrictive political and regulatory frameworks, among other considerations. Between 2001 and 2010, innovations were responsible for agricultural production growth of almost 2.0 percent. In the past decade they have only accounted for 1.3 percent.[16]
- Agricultural land use growth therefore increased again. While little additional land was added around the millennium, it now accounts for almost 20 percent of output growth.

Sources of growth in global agricultural output between 1961 and 2020 (in percent per annum)



Source: Own figure, based on USDA (2021).

16 We can attribute a particular role to increased political control via technology-inhibiting regulations in high-income countries such as those in the EU and subsequent spillover effects in low-income countries, which are already reported to have contracting TFP (Steensland, 2019).

In essence, this means that if innovations are not increasingly implemented, we will lean on expanded land use to produce a considerable share of output growth to feed the world over the next decade(s). Better technologies, i.e., technical innovations, are therefore essential to avoiding additional negative consequences in terms of climate change, biodiversity loss and the destruction of natural resources (see also Kockerols, 2022; Peters et al., 2022; Fuchs et al., 2020; Beltran et al., 2021; Paarlberg, 2022).

How should natural and technical resources be used though? Here, the fundamental idea should be that we use them because we need them. Any use for agricultural purposes must be understood as an intervention in natural systems that results in environmental costs. It is how they are used, rather the use itself, that must be given higher priority in political debate.

Input – output ratios

The basic equation of the policy debate is simple. On the one hand, we need sufficient agricultural output to satisfy global food demand. On the other, we must use inputs efficiently in doing so. The optimal ratio between output and input is the key. Mathematically speaking, we must produce a certain output with minimised input, or maximise output with a certain input. Economists also use the term "productivity" to describe the ratio between them. Higher agricultural productivity enables us to meet a broad spectrum of policy objectives, including increased food security through more output and less environmental damage through less input.

Both elements can be targeted by innovations. Bureau and Anton (2022) state that *"Productivity is a key indicator […] and captures the ability to produce 'more with less' […]. This can be achieved either by technological change or by changes in efficiency."* This is what we call innovation. These new and better technologies can reconcile needs for increased agricultural productivity with environmental concerns. The importance of technological innovation[17] in meeting agricultural policy objectives is discussed in the box below.

17 The examples mentioned merely refer to innovative technological progress. Increasing TFP in particular, and productivity in general, however, are also subject to technical efficiency, i.e., the better use of resources. Behavioral innovations in terms of farm management, private as well as public decision-making, market actor communication, etc., also play a key role. Many economic problems on farms and environmental challenges are management-related and can be over-come by innovations in farm management, structures and logistics. It is also worth noting that many agricultural and food security challenges currently faced, mainly in low-income countries, are in many ways comparable to the situation in Europe more than a century ago. Structural and technological innovation and change enabled Europe to become food secure and economically prosperous, all while addressing environmental concerns such as European deforestation (see, e.g., Aerni, 2018).

The particular importance of innovation in meeting agricultural policy objectives

Here, we highlight the importance of having technology in the pipeline. We emphasise crop production technologies and give examples of plant breeding, plant protection, and plant nutrition innovations that allow for better use of inputs in terms of technical efficiency. All of them can positively change the ratio between output and input, i.e., have a positive impact on agricultural productivity and environmental concerns.

Selected plant breeding innovations

Plant breeding can be considered a continuous process of developing innovations: to be released, each new variety must be better than varieties that are already available. The potential impacts of new varieties currently being developed through new plant breeding techniques (NPBT) illustrate how very specific genetic crop improvements can lead to remarkable benefits at both farm and societal levels if successfully implemented.

Meanwhile, there is much evidence to show that plant breeding in general and NPBT in particular offer substantial innovations that improve productivity. Some examples illustrate the potential benefits:

- Fungi-resistant wheat (see, e.g., Boldt, 2020; Noleppa and Cartsburg, 2021; Sánchez-León et al., 2018; BDP, 2021; Zetzsche et al., 2020) and grapevine varieties (see, e.g., Bruins and Morgante, 2021; Malnoy et al., 2016; Noleppa and Cartsburg, 2021; Wang et al., 2018; Wan et al., 2020) developed through NPBT, for instance, may considerably reduce the number of fungicide applications in European agriculture, thus contributing to better environmental protection while maintaining yield levels.

- Pod shatter-resistant OSR varieties (see, e.g., Young et al., 2018; Braatz et al., 2020; Noleppa and Cartsburg, 2021; Østergaard et al., 2021), virus-resistant sugar beet varieties (see, e.g., Stevana-to et al., 2018; Galein et al., 2018; John Innes Centre, 2021; Noleppa and Cartsburg, 2021) as well as drought-resistant maize varieties (see, e.g., Noleppa and Cartsburg, 2021; Shi et al., 2017; Njuguna et al., 2017; Liu and Qin, 2021) bred with modern sophisticated technologies, can even increase yields remarkably, thereby minimising pressure on scarce natural resources such as arable land.

It is not the individual NPBT application that should count, however, but rather the overall potential these technologies have to contribute to the plant breeding progress in general and over time. The mere time savings embedded in NPBT due to accelerated trait integration and early generation selection will be substantial (see, e.g., Jarasch, 2019; Zaidi et al., 2020; Noleppa and Cartsburg, 2021) and certainly lead to considerable growth in additional yield and productivity. NPBT will contribute to the achievement of ambitious goals such as those outlined in the two strategies at the European scale, and the UN's 2030 Sustainable Development Goals at the global scale (see also Tolu, 2022; Peters et al., 2022).

Selected plant protection and plant nutrition innovations

EUIPO and CPVO (2022) argue that plant breeding-induced innovation accounts for a large, if not the largest, part of all productivity growth generated in arable and horticultural farming, at least in the EU and over the past 25 years. We should not neglect other innovations that also offer significant progress though. The following examples from plant protection and plant nutrition illustrate their importance:

- “Precision farming,” “site-specific farming,” “grid farming,” “smart farming,” and “variable rate application” refer to technological solutions that allow farmers to substantially reduce the input of pesticides and also fertilisers per unit of land without losing yield, thus optimising the ratio of output vs. input by minimising input use. In a recent analysis, HFFA Research (2022) was able to show that technologies already available in a German and EU context have the potential to reduce the use of fungicides by 27 percent and of mineral (nitrogen) fertilisers by 21 percent. In weed management, a reduction of more than 60 percent can be achieved. For specific plant protection and plant nutrition technologies and the related impacts on reduction and also emission goals, see, for instance, Alix et al. (2017); Artner-Nehls et al. (2021); Belafoutis et al. (2017); Castaldi et al. (2017); Dehler (2020); Gandorfer et al. (2017); HFFA Research (2022); Hülsbergen (2019); Janke et al. (2020); Kempenaar et al. (2018); Lieder et al. (2021); Loddo et al. (2019); Ørum et al. (2017); Pohl et al. (2021); Rajmis et al. (2021); Tackenberg et al. (2017); Warnecke-Busch et al. (2020); Whetton et al. (2018).

- Pesticides and novel fertiliser innovations are also noteworthy. Biopesticides, for instance, based on active naturally occurring or synthetically derived ingredients of natural origin (CropLife Europe, 2022), help reduce chemical pesticides and associated environmental risks while maintaining yields (Dent, 2021). Similarly, biofertilisers – containing living microorganisms that, when applied to soil, a seed, or a plant surface, colonise the rhizosphere and so promote growth and availability of nutrients for the host plant – have emerged as a more environmentally friendly and sustainable alternative to chemical fertilisers (Chaudhary et al., 2020).

- Synthetic chemical pesticides will also remain important. Novel active ingredients are being developed often and help to maintain and increase yields while reducing environmental and health risks that may be associated with improper use. In the past decade alone, at least 105 chemical pesticides have been launched or are currently under development: 43 fungicides, 34 insecticides/acaricides, six nematicides, more than 20 herbicides, and one herbicide safener (Umetsu and Shirai,2020).

Improvements in food systems also increasingly rely, for example, on digital technologies. Digital solutions help improve yields, reduce food losses, and support farmers in getting a fair return by providing instant knowledge exchange that can counter information asymmetries and reduce inefficiencies and transaction costs (World Bank, 2021).

Innovation is not only about technologies, however, but also about management practices that can help farmers address environmental risks and reduce socioeconomic impacts. Holistic risk and resilience management means creating an environment conducive to investment in risk mitigation measures (e.g., application technology, riparian ecological infrastructures), and to developing farmers’ abilities to adapt and transform their practices (e.g., education). It is not just about focusing on reducing the use of technologies regardless of the relevant geographies and environmental pressures.

Many countries worldwide have shown that technology and sustainable intensification can significantly improve natural resource use, emissions reduction, risk mitigation measures, biodiversity protection, and the well-being of local communities. Several countries are adopting innovation-based approaches towards sustainable agriculture and actively fostering innovative ecosystems that allow agricultural innovation to flourish. Aerni (2009), for instance, illustrates concrete cases of how recent technologies can be applied to increase food quality and reduce the environmental impact of agriculture. Wax and Anderson (2021) consider this an "embracing innovation" approach, and Paarlberg (2022) names it a science-forward path of agricultural development. The associated methods are not resource-intensive, but information intensive (Paarlberg, 2022), and we fully support this vision.

This vision should not neglect the fact that while technologies focus on increasing agricultural supply, more long-term measures primarily aimed at reducing food and additional demand also exist. They include targeting dietary change by encouraging consumers to eat fewer animal-based foods, reducing food waste and loss and optimising biofuel policy. These topics should also be considered innovations from a behavioural, managerial and structural perspective.

5. CONCLUSION

In some high-income countries, the priority for agricultural policy has progressively shifted over the past decades to focus on sustainability rather than production and productivity. In the EU, the Europe-an Green Deal and its F2F Strategy and Biodiversity Strategy looks to drive a significant acceleration towards a more sustainable and resilient food system.

At the same time, the Russian war in Ukraine and the COVID-19 pandemic have recently highlighted food system vulnerabilities to supply shocks that can ultimately lead to a global food security crisis. The associated volatility in food quantity and price is compounded by the uncertainty surrounding production quantities, which are affected by increasingly frequent and severe extreme weather events due to climate change. A tighter global food supply and more volatile markets lead to increasing scarcity, which will likely persist in many regions of the world.

While increasing the sustainability of agricultural processes is a noble pursuit that needs to become reality - continuous improvements and innovation in agriculture and the food sector are necessary to foster economic prosperity, as well as a healthy population and planet – we must nevertheless give the same weight to the achievement of food security in policy formulation and implementation. We otherwise risk jeopardising the achievement of the UN 2030 SDGs and creating major disruptions at both regional and global levels.

Several impact assessments suggest that the EU's F2F Strategy and Biodiversity Strategy will have a quantitative impact on agricultural productivity, food availability, farm production costs, and societal welfare. Food availability could shrink for as many as 190 million people due to the supply-side effects of the two strategies, making the impact of the European Green Deal potentially ten times larger than the food security impact we now face.

If the strategies of the European Green Deal are not properly managed, their market and trade distortions could create new challenges for states and societies. In an extreme scenario, the introduction of mirror clauses could damage competitiveness, trade and, ultimately, food security, especially in low-income countries and for the vulnerable populations of wealthier nations.

Lower European production is likely to lead to increasing agricultural production outside Europe. De-pending on where it takes place, this geographical shift could undermine many of the plan's environ-mental benefits. Millions of hectares of natural or semi-natural habitats outside the EU would likely be converted towards agriculture and the negative net impact on biodiversity and GHG emissions would be significant.

Where does this leave us? We believe that the situation calls for a comprehensive response incorporating multiple elements. We recommend that the global community envisage the following actions.

Reinstate food security as a global policy objective

We strongly argue that food security at the global scale must be reinstated as a non-negotiable objective in the agricultural and food policies of wealthier nations. The implication for the EU's F2F Strategy and Biodiversity Strategy is a reformulation of overall goals so that both regional and, critically, global food security is acknowledged as an overriding imperative alongside environmental goals (see also Schiavo et al., 2021). We agree with von Cramon-Taubadel (2022) who argues that it is not sufficient to make European agriculture more sustainable ecologically, we must also ensure economic productivity and prosperity at the global level. This does not mean that we will no longer address environmental concerns and other challenges such as animal welfare in our quest to produce highly nutritional, safe food for the world's population. As responsible actors committed to helping to meet today's challenges, EU member states and other countries must consider all economic, social, and environmental concerns in a balanced way.

Support additional studies and extensive research globally

Given the evolving situation, and in light of the far-reaching potential implications, we strongly recommend that individual countries perform their own local impact assessments of the European Green Deal and its policies. They need to consider socio-economic issues as well as environmental aspects, examine the potential effect of changes in agricultural input (fertilisers, pesticides, etc.) and land use, as well as reflect on mirror clauses in international trade. This requires that "Sustainability" be correctly interpreted and conceptualized as a methodology that integrates and measures the costs and benefits of the technical decision's impact on environmental, economic and social pillars. We also recommend that countries further explore the role of innovation in achieving greater economic, social and environmental sustainability of agriculture. Such new studies are essential to the development of sound agricultural and food policies. Research allowing us to thoroughly investigate the trade-offs between domestic production and consumption, as well as subsequent imports and exports is critical (Fuchs et al., 2020), as is a more complete analysis of policy and other targets (Beltran et al., 2022). Options targeting agricultural and food demand such as changes in dietary habits, lowering food waste and loss and amendments in biofuel policy should also be explored in detail.

Greater data availability would enable researchers to quantify the impact of a policy on food systems across multiple aspects of sustainability. Methodological advances could then translate these insights into concrete policy and governance options, allowing food systems to achieve more efficient and sustainable outcomes.

An impact assessment of the still qualitatively formulated demand-related objectives of the two strategies is also necessary to complement the quantitative evaluations of the supply-focused objectives and measures. The effect of dietary changes, for instance, has not been considered by the cited impact assessments (see Wesseler, 2022). Available approaches could nevertheless fill this gap (see e.g., Schiavo et al., 2021).

Expand dialogue, improve communication

Identifying unintended consequences and exploring possible solutions for reconciling any conflicting agricultural and food policy objectives requires a holistic, systemic, and global approach. Today's challenges are global and all actors must be welcomed into the therefore necessary dialogue: the goal is to promote global food security while ensuring that no one region's policies impinge on the development and livelihood of another. Diverse agricultural needs and specificities need to be given equal weight in the analysis of the costs and benefits associated with agricultural and food policy formulation and implementation.

The future of agriculture cannot be determined by politicians in isolation. All actors, including farmers, food chain operators, policy makers, and civil society should be part of the discussion and, ultimately, the solution. Society demands a shift towards more environmentally friendly agriculture. While this will cause both real and opportunity costs, consumers still want to buy food and other agricultural products at affordable prices. Consequently, if agriculture is to change, societal demands must change too. Formulating partially contradictory societal goals will not lead us anywhere: we must instead seek and communicate solutions that create synergies between the goals, factor in the political and socio-economic realities at local, regional, and global levels, and avoid associated trade-offs.

The complexity of the issues and the magnitude of the challenges we face also require that we overcome the polarisation of public debate on agriculture and food. All too often, individual, narrow perspectives dominate and focus solely on the environment or on the economy. Now, we must bring the different points of view together to create holistic discourse. Much would be gained if we, as a society, understood that agriculture is a sector that must deal with precise, very challenging and, unfortunately, sometimes contradictory demands. Addressing this will require actors with opposing or divergent views to engage in dialogue, broaden their perspectives and be open to the criticism of the other side.

Policymakers must also communicate more clearly: it is not enough to address problems openly and formulate challenges, they must also define realistic goals for overcoming challenges and then support them with concrete and targeted implementation measures. Demand for blanket reduction targets with respect to some technologies without properly formulating implementable measures or evaluating intended and unintended consequences cannot be considered targeted policy making.[18] Raising public awareness is another effective tool for supporting policy. Policymakers should support interdisciplinary research and evidence-based information campaigns.

Integrate and support innovations and technologies

Unsolved and pressing problems related to issues such as climate change, protection of the environment and biodiversity and animal welfare will not disappear. The fundamental changes in both individual behaviour and policy making that are needed to achieve more sustainable agricultural and food systems will undoubtedly take considerable time. We must therefore call on the wide range of technological possibilities available to us to bridge this obvious gap.
Achieving socio-economic and environmental sustainability objectives along with food security goals will mean breaking the historical pattern of increasing agricultural outputs by expanding farmland and increasing input use. The solution is to increase productivity. That is, we must produce more with less through innovation.

18 This concern about blanket reduction targets is shared in recently published science briefs commissioned by the secretariat of the Convention on Biological Diversity (CBD) (Archer et al., 2022). During the ongoing negotiations of the Global Biodiversity Framework, the EU is strongly advocating for the introduction of certain pollution reduction targets as formulated by their own Biodiversity strategy to become global objectives. The authors of the briefs are clear in their recommendation: pesticide policies should be framed in terms of risk, not just numerical targets, and measures to reduce pollution should be adapted to national contexts. They also caution that reductions in fertiliser and pesticide use leading to reduced agricultural productivity could result in a loss of natural habitats through land use change.

The greatest potential comes from improvements in technologies and management. Innovations in plant breeding, plant protection and nutrition, as well as in management techniques aimed at in-creased agricultural and food productivity while addressing environmental issues should be put into more widespread use. We recommend the continued integration of improvements in chemistry, genetics, weather forecasting, equipment, farm management, etc., into agricultural production systems. New approaches such as digitalisation, NPBT in general and gene editing in particular should be promoted as indispensable tools in achieving the formulated goals. Introducing new chemical and novel non-chemical solutions and applying optimised practices that better respond to local vulnerabilities and reduce environmental impacts is clearly necessary. All of this must therefore be supported politically in the EU as well as at the global level.

Many sources have highlighted the role of innovation, and this cannot be emphasized enough. Most recently, at the G7 Ministerial Conference in Germany, participants called on countries to foster policies that increase productivity, efficiency, resilience, and inclusivity of agri-food systems and support the necessary investment in innovation (FAO, 2022c).We therefore believe that a synergistic combination of policy interventions and a particular emphasis on innovation are needed to increase global food security while reducing the environmental impact of our food systems. We agree with several studies (see, e.g., Springmann et al., 2018) that have shown that single measures will never be sufficient to mitigate the projected increase in environmental pressure while providing enough food on a global scale. Instead, combining improvements in technologies and management to increase agricultural productivity and yields while targeting dietary change and food loss reduction could lead to an overall increase in the global food supply of up to 223 percent (Kummu et al., 2017). While the most significant potential comes from closing the yield gap through innovative technologies and improved management, changing dietary habits, and reducing food loss and waste also have significant potential to increase food availability over the longer term.

Technologies should therefore be seen as a major part of the solution, not the problem. Recognising this in public and in private decision-making would be an innovation itself and open win-win opportunities for agriculture, food security, and the environment. Achieving this will not be possible, however, without proper policy that actively supports and drives the social acceptance of innovative technologies, born from the joint effort of public institutions and private business.

Formulate meaningful regulation

A proportionate and results-oriented regulatory framework is needed to provide clear and consistent rules for innovation in the agricultural and food sector. We must apply all available and ("safe") technologies to increase output and decrease the use of resources. This requires a reinforcement of the overall policy and regulatory framework to encourage, and certainly not hinder, the necessary investments into future innovations. In this respect, the F2F Strategy of the EU already acknowledges that the latest Research and Development (R&D) and subsequent innovative technologies may play a more critical role in increasing environmental and socioeconomic sustainability. What is still missing are concrete policies and measures for realising the specific strategic aim of advanced R&D.

Such a regulatory framework should encourage European innovation hubs such as plant breeders and the crop protection and plant nutrition industries to devote the necessary resources to increasing economic productivity and environmental resource efficiency. Safety considerations should therefore relate to individual technologies and their application as well as the characteristics of the resulting product, rather than being applied to whole groups of technologies. The implementation of novel tools such as NPBT, and the associated development of innovations such as climate adapted seeds and biological pesticides, which could replace current technologies, should be assessed.

Evaluations should not, however, be dominated by EU ambitions on environmental sustainability. They should also include food security criteria and promote a balanced judgement. The overlap between horizontal legislation such as Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) or the Chemicals Strategy for Sustainability and requirements concerning, for instance, the placement of pesticides on the market, must be considered a challenge to the use of innovative technologies and products.

Final recommendations

To promote a sustainable agricultural and food systems agenda that avoids the pitfalls of major unintended consequences, we recommend a more progressive policy mix that sets quantitative targets, but also enables environmental transition without the sacrifice of economic productivity. This will entail:

1. An agenda for technology development that highlights digitalisation and biotechnologies for agricultural inputs, i.e., new plant protection solutions, novel plant nutrition products and, of course, innovative seeds;
2. An agenda for promoting innovation in crop and livestock production, consumption patterns, trade flows, local and global resource use, farm management, and value chains;
3. An agenda for reducing production and supply risk that is based on objective scientific facts, not perceptions.

In conclusion, we recommend that food security be reinstated as a central objective in agricultural and food policies; that more research into the potential for unintended consequences be carried out on a global level; that policymakers open the dialogue more widely and improve communication; that technologies and innovation be more widely promoted and spread, and that innovation be supported by an appropriate regulatory and policy framework. This global approach offers our best hope for realising sustainable agriculture that provides sufficient food at reasonable prices for all people.

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