Adding mirror clauses within the European Green Deal: Hype or hope?

Alexandre Gohin*, Alan Matthews**

*UMR SMART INRAE Institut Agro, Rennes

**Trinity College Dublin

Abstract

Proposed reductions in farm input uses foreseen in the European Green Deal may penalize European farm production while increasing environmental leakages to foreign countries where production may expand. These expected impacts have led to calls for a more restrictive trade policy based on mirror clauses. This paper considers as a case study a potential ban of glyphosate in vegetable and fruits production. We develop an original computable general equilibrium model with endogenous adoption of new European production standards by foreign producers on currently latent markets. We find in our case study that adding mirror clauses to the Green Deal marginally improves European farm income and the global environmental footprint of food. We find that foreign producers as a whole can gain from these clauses and not lose as in a standard analysis. European households support these clauses by paying higher food bills while consuming vegetables and fruits produced without glyphosate.

Introduction

The European Green Deal and its implementation in the agro-food sector, the Farm to Fork and associated strategies, sets ambitious targets to reduce dependency on pesticides and antimicrobials, reduce excess fertilisation, increase organic farming, improve animal welfare, reverse biodiversity loss as well as contribute to the objective of a climate-neutral Union by 2050. Several impact studies have assessed the consequences for agricultural production and farm incomes in Europe as well as the impact on global markets of several of the measures making up the Farm to Fork Strategy (Wesseler 2022). While limitations of these studies have been identified (Barreiro-Hurle et al. 2021), there is a broad consensus that fully implementing the Strategy by 2030 would mean lower EU production relative to a baseline, though there is greater disagreement over the likely impacts for farm incomes and trade. However, most studies project a higher level of net imports and thus the potential for environmental leakages to those countries where production will expand.

These potential impacts have led to an unlikely alliance between farm organisations and environmental NGOs calling for a more restrictive trade policy to accompany implementation of the Green Deal through the use of mirror clauses (Baldon et al. 2021; Matthews 2022). Mirror clauses would make market access conditional to compliance with domestic environmental, animal welfare or health standards and regulations. Farm organisations seek to offset the potential loss of competitiveness vis à vis third country exporters by calling for a level playing field. Environmental NGOs support a more restrictive trade policy because it would help to avoid an increase in imports and thus the export of the environmental footprint of production to countries where it is assumed lower standards are in place. Environmental leakage of this kind could even lead to an increase in global emissions and environmental harm despite the raising of standards in the EU.

The European Commission in its recent trade strategy has endorsed the potential use of mirror clauses provided that this is done in full respect of the relevant WTO rules (European Commission 2021). In a more recent report, the Commission recommended performing ex ante legal and economic cost-benefit analysis of potential mirror clauses (European Commission 2022). In this context, the main objective of this paper is to provide a quantitative assessment of a potential standard banning the use of glyphosate in EU vegetable and fruit (v&f) production while also meeting the Green Deal objectives to reduce use of chemical fertilisers and pesticides in this sector. The choice of this case study is motivated in the first section. The methodology developed to analyse mirror clauses is summarised in the second section. The scenarios are defined and analysed in the third section, followed by a discussion of the results. The final section reflects on our findings and draws conclusions for further research.

Motivation of the case study

The glyphosate active substance

Glyphosate is the most frequently used active substance, both worldwide and in the EU, to combat weeds that compete with cultivated crops. Glyphosate-based pesticides are also used as a pre-harvest treatment to facilitate better harvesting by regulating plant growth and ripening.[1] In current European legislation, glyphosate is recognized as an active substance which can cause serious eye damage to glyphosate applicants and is toxic to aquatic life but does not pose a carcinogenic threat to humans. Moreover, when used according to good agricultural practices, it does not pose an unacceptable risk to the environment. Accordingly, this active substance is currently approved at the EU level while EU Member States are responsible for the authorization and use on their territories of glyphosate-based pesticides.[2] Imports of foods with residues of this active substance by way of import tolerances can also be permitted. Such import tolerances can be granted provided

[1] While glyphosate is predominantly a herbicide, here we follow convention by describing all crop protection products such as insecticides, herbicides and fungicides as pesticides.

[2] So far, only Luxembourg implements a complete ban on glyphosate use in its farming sectors from 2020.

the reason for non-approval in the EU is not related to the protection of consumer health and provided a risk assessment is undertaken by the European Food Safety Authority (EFSA) to show that the proposed import tolerance is not a risk to consumer health.

Looking ahead, conditions for the future use of glyphosate in the EU are uncertain. Active substances are normally approved at the EU level for a 15 year period. Glyphosate use was approved in 2017 for a 5 year period only, in order to take account of the insights of newly launched studies assessing its health and environmental effects. However, ongoing evaluation of the potential health and environmental risks of the substance by the European Chemicals Agency and the European Food Safety Authority will not be completed until at least mid-2023 due to the volume of comments received on its draft assessment report.[3] In addition to scientific uncertainties, there are also policy uncertainties linked to the future positions of the different policy makers, both at the EU and member state levels. For example, the European Parliament officially asked in 2021 for a complete phase out of glyphosate use in farm sectors.

Glyphosate use is under scrutiny not only in EU countries but in most countries in the world. This is partly linked to the declaration in 2015 by the International Agency for Research on Cancer (IARC) that glyphosate is a possible human carcinogen. Focusing on the US case, glyphosate-based Roundup manufacturer Monsanto (later purchased by Bayer) has been battling thousands of lawsuits alleging that the product caused non-Hodgkin's lymphoma. Similar to the EU case, a growing number of US states and cities have been restricting or outright banning the use of glyphosate but the US federal government currently maintains that glyphosate is safe to use. There

[3] https://food.ec.europa.eu/plants/pesticides/approval-active-substances/renewal-approval/glyphosate/assessment-group_en

is the additional concern in the US that the resistance of weeds to glyphosate increases, lowering the private and social values of glyphosate (Van Deynze et al., 2022).

We are not in position to anticipate which countries will move first to a potential ban on glyphosate, if any. With the Green Deal, the EC indicates that it wants to lead the change towards greening our economies, with the hope that other regions will follow the EU example. In this context, an *ex ante* analysis of a first-mover EU glyphosate ban is therefore appropriate.

The fruit and vegetable sector

Glyphosate is used for many crop productions but we focus our analysis on the vegetable and fruit sectors for the following reasons. First, imposing a ban on an active substance requires the ability to control its effective absence in products sold on the EU internal market. EU Regulation (EC) No. 396/2005 on pesticide residues defines how maximum residue levels (MRLs) for active substances are set. MRLs are established solely on health grounds and do not consider environmental risks (which is required when approving an active substance). Each year, EFSA and related Member States agencies control for the presence of approved and unapproved active substances. This procedure is performed particularly on vegetable and fruit products because they are often directly consumed by households and past controls reveal that samples can exceed the relevant MRL. This means that the technical feasibility mentioned by the Commission in its cautious report evaluating the potential use of mirror clauses should not be a problem.

Second, there are growing pressures across all EU Member States to increase vegetable and fruit consumption and to reduce animal protein consumption. This shift in consumption is presented as a way to improve the sustainability of the food system, tackling simultaneously the climate, environmental and public health challenges. Even if the Green Deal roadmap does not explicitly include provisions to encourage plant-based diets, assuring EU consumers of the absence of residues of controversial active substances in these products could be one way to encourage consumption. Residues from all pesticides are currently detected in around 45 per cent of controlled samples of food products and MRLs are not satisfied in 5 per cent of these samples. Among all active substances, glyphosate residues are currently detected in around 2 per cent of the controlled food products, with exceedance of the MRL by less than 0.6 per cent. The highest occurrence of exceedance is observed on dry lentils which are a flagship product of the green transition. Banning the use of glyphosate in vegetable and fruit production may be a measure implemented to sustain the consumption of these products and may be a compromise between a simple renewal of glyphosate authorisation and a complete ban of glyphosate for all uses, though it will also likely increase their price, something that we quantify later.

The choice of our case study is finally also dictated by data considerations. Other mirror clauses are also under scrutiny, such as for antibiotic uses in animal productions and neonicotinoid insecticides in many crop productions. But the technical and economic data required to perform CBA for these potential mirror clauses are currently less available.

Methodology

The economic literature assessing the market effects of agricultural production standards and associated trade measures is large and vivid. Many economic models already simulate the ex ante market and welfare effects of the targeted input reductions of the Green Deal by introducing endogenous levels of input taxes (Wesseler, 2022). This modelling approach does not ensure that some undesirable inputs (such as unapproved active substances) are no longer used: the taxes may simply reduce their uses, not remove them. Moreover, the eventual introduction of mirror clauses due to potentially new EU production standards is not a policy measure that requires comparable input taxes in foreign countries who wants to export to the EU. Rather, a mirror clause is implemented only if the standards can be controlled (such as the absence of a particular active substance in some food products). This means that not all producers in foreign countries may need to comply with the new EU standards, only those willing to export to the EU markets. This likely leads to additional certification and segregation costs in the food chain, as well as different production costs for the different active technologies that are ultimately reflected in different output prices and/or different factor returns.

These different costs have been collected by Beckman et al. (2021) to analyse the trade dispute between the US and EU on cattle fed with growth hormones, a prohibited practice in the EU. These authors simulate the market and welfare effects of the removal of this mirror clause with the Global Trade Analysis Project (GTAP) CGE model. However, this model does not differentiate the production technologies used for beef sold on the US market and as exports to the EU. Accordingly they develop an imperfect solution by converting all additional observed costs as export and import taxes between the US and EU. This approach is imperfect as it does not explicitly recognize that the feed efficiencies are different across the two technologies, nor that some US households (as well as households in other countries) may also value and consume hormone free beef cuts (Drouillard, 2018).

Beckman et al. (2022) use the same GTAP model to analyse the choices of non-EU countries to adopt or not the new standards that the EU may implement with the Green Deal. Again these authors do not recognize the possibility that only some producers in non EU countries adopt the new standards and that some non EU households also want to consume products offered by the new production standards. Rather they assume a fixed number of technologies and commodities, and that adopting foreign countries implement input taxes such as to reduce their aggregate input usage while non-adopting ones face a purely ad hoc increase of import taxes to the EU by 50 per cent.

To perform the analysis in our case study, we develop an innovative CGE modelling approach that overcomes these limitations. We endogenize the number of technologies (representing different production standards) as well as the number of commodities where we distinguish between conventional vegetable and fruit production (labelled conv v&f) and glyphosate-free production (labelled gly-free v&f). Our method allows an exporting country to continue to produce using conventional techniques but it may also opt to produce the higher-standard product when it becomes profitable to do so. The approach relies on latent demands (in this case, for gly-free v&f production) to become effective depending on economic conditions.

The empirical application is based on a modified version of a conventional CGE model using the GTAP 10 database aggregated into three regions: EU, US and ROW. The main innovation is to permit output in the vegetables and fruits sector to be produced using two technologies: the conventional technology (conv v&f) and a latent technology without the use of glyphosate (gly-free v&f) which is more costly and also with reduced yield compared to conventional production. This dual technology approach is implemented on the supply side using a microeconomic approach inspired by Carpentier and Letort (2014) and previously implemented in a CGE model by Bareille and Gohin (2020). At the demand and trade sides, we implement a Normalized Quadratic Expenditure System (NQES) which allows for latent demands and trade flows. A full explanation of the modelling framework and the calibration procedures are provided in the accompanying supplementary information.

Scenarios and results

This model is used to simulate the impacts of introducing a glyphosate ban and reducing chemical uses in the EU for the production of v&f with and without a mirror clause. Several variants are also run to test the sensitivity of the results to specific assumptions. The consequences for production, prices, trade and incomes are compared for each scenario.

The first scenario, called the Green Deal, introduces two instruments: a ban on glyphosate use by European v&f producers and an input tax on other chemical input used in this sector. Other chemicals can also be used by glyphosate-free v&f producers as we do not assume that this production is organic. The level of this tax is calibrated to obtain the desired reduction of chemical uses (by 35 per cent in our case study, where we aggregate both mineral fertilizers and pesticides). This approach with a tax is shared with all studies that have already simulated the impacts of the Green Deal. This first scenario is obviously much simplified compared to the many provisions in the EU Green Deal but it is adequate to reveal the market and welfare impact of mirror clauses. This is the subject of our second scenario, called the mirror clause, where we introduce the same two instruments plus an EU import ban on conv v&f. This is equivalent to a ban on intermediate and final demand of conv v&f on the European market. Foreign producers can only serve the European market with gly-free v&f, and must incur additional identity/preservation costs to do so. In this second scenario, the level of the EU input tax is again adjusted to ensure a reduction of chemical uses by 35 per cent.

Impacts of the Green Deal scenario

Table 1 reports some market impacts. By definition, European conv v&f production disappears with this scenario, as well as European exports to foreign markets, but European demand for conv v&f products continues to exist. The intermediate demands of conv v&f by European processing firms fully switch to imports and the final demand by European households drops by 76.9 per cent. This is only partly replaced by gly-free v&f whose simulated consumption amounts to 68.1 per cent of the initial household demand. This is explained by the higher prices of both foreign conv v&f and European gly-free v&f (by 12.6 per cent). European gly-free v&f production amounts to 59.5 per cent of initial production, mostly explained by a decrease of v&f acreage (by 33.7 per cent). European v&f yield decreases by 6.7 per cent, mostly due to a switch towards the gly-free technology. The price effects on yields (reduction of 0.2 per cent) are limited because the increase of the output price partially compensates the input tax.

As already obtained in previous studies, this scenario benefits foreign producers (by around 3 per cent) for two reasons: an increase of European imports (close to 100 per cent) and the cessation of European exports to foreign markets. On the other hand, the final demands in foreign countries slightly decrease (by less than 1 per cent). The price effects are not sufficient to justify gly-free production in the US.

Table 2 reports some "welfare" impacts, starting with total chemical use (in volume) in the v&f sector and by all farming sectors[4]. Chemical use by the European v&f sector decreases as defined in our scenario, thanks to a huge input tax of 270 per cent. This may appear very large but chemical expenditure represents only 3.5 per cent of v&f output in the GTAP database. Moreover, the price of gly-free v&f increases, partially tempering the effects of the input tax. In other countries, chemical uses by their conv v&f sector increase in proportion of their production, due

[4] We do not perform a full cost benefit analysis and welfare analysis because our (static) methodology does not capture all environmental (such as biodiversity) and health effects.

to the more limited price effects. Global use of chemicals by the v&f sector increases by 1.5 per cent. This result is explained by the lower European use of chemicals per unit of v&f output compared to other countries in the GTAP database. This result confirms the fears expressed by NGO of environmental leakage. We find this occurs also at the global farm level. Indeed, the reduction of European v&f production leads to a small increase of other crops, such as cereals, and hence use of chemicals in these sectors. The cross sector effects are of the opposite signs in other countries (for instance, a reduction of US production of cereals). Globally, the volume of chemicals increases by 0.5 per cent with this scenario. This result is consistent with some previous studies that removing glyphosate may end up with greater use of chemicals in the farm sector (Ye et al., 2021).

The next columns of Table 2 report the impacts on farm incomes (the returns to primary factors of production, namely labor, capital and land). As expected, we find that European farmers suffer from this scenario, by 24 billion dollars. This is supported in our medium term horizon by a decrease of the land return (by 8 per cent) and mostly the capital return (up to 51 per cent). Conversely, farmers in other regions gain. In percentage terms, these figures are not marginal.

The last columns of Table 2 report the impacts on food bills. Again, we find increases in v&f expenditures, with larger effects in Europe due to larger price effects. More surprisingly, we find a decrease in European food expenditure that is explained by both a 0.4 per cent decrease of European household income and small price decreases of other food products (for instance, by 0.4 per cent for beef). In other countries, these effects are reversed, leading to higher food bills. We also find that the wages of European unskilled workers noticeably decrease (by 0.7 per cent), linked to the reduction of European overall activity. The opposite occurs in the Row (by 0.1 per cent).

Overall, these results are qualitatively consistent with available results of studies evaluating the Green Deal, and quantify fears expressed by NGO and European farmers regarding the global environmental and farm income effects.

Impacts of the mirror clause scenario

Relative to our Green Deal scenario, the mirror clause scenario also bans the European import of conv v&f. The European input tax is also adjusted endogenously to ensure that the 35 per cent reduction of chemical use in the v&f sector is achieved.

The market impacts of this scenario are reported in Table 3 and compared to those of Table 1. This mirror clause scenario simultaneously decreases the demand for conv v&f and increases the demand for gly-free v&f. This leads to a higher price of gly-free v&f. The European price is 29 per cent higher than the initial conv v&f price (compared to 13 per cent in the previous scenario). This has nevertheless a very modest additional impact on the European gly-free production: it represents 60.3 per cent of initial production (compared to 59.5 per cent in the previous scenario). This is explained by the higher input tax required to avoid the rebound effect on input use (more on this rebound effect in the discussion).

The higher European gly-free price also translates to a higher gly-free price in the USA, such that USA farmers start producing gly-free v&f. This corresponds to 59.4 per cent of their initial v&f production. This new production partly substitutes their production of conv v&f (a decrease by 45.9 per cent). This cross supply effect is much larger than the loss of US exports of conv v&f to European markets. Hence the US price of conv v&f increases by 8.4 per cent (compared to 1.4 per cent in the previous scenario). This price increase penalizes US consumption (by 3.1 per cent) and US exports to the RoW (-73.4).

The effects are much simpler on the RoW markets. By assuming by default their inability to identify and segregate their potential gly-free v&f, RoW producers of conv v&f face two shocks: a stop of their exports to European markets on one hand, and a significant reduction in competition from US production. Overall, we find that the RoW price of conv v&f slightly increases (by 0.6 per cent), RoW production slightly increases (by 1.5 per cent) with the additional output sold on the US market (an increase of 88 per cent).

Some welfare impacts of this scenario are reported in Table 4 and compared to those of Table 2. By definition, we obtain similar figures for European farm use of chemicals. On the other hand, we find a significant increase in chemical use by the US v&f sector (by 20.2 per cent), which is explained by an increase of US global production of v&f and an increased share of gly-free production (that requires more chemicals to produce the same amount of v&f). By contrast, chemical use increases less in the RoW, similar to the output effect discussed above. Overall, world use of chemicals by the farm sector increases slightly less (0.4 per cent compared to 0.5 per cent in the previous scenarios), with also a smaller amount of glyphosate. The addition of mirror clauses to the Green Deal thus moves the global economy towards NGO concerns but not enough to compensate for the Green Deal impacts.

We find that the impacts of the mirror clause scenario on European farm income indicators remain negative, with modest gains with respect to the Green Deal scenario (by 0.9 billion dollars). This is linked to the higher input tax to avoid the rebound effect on chemical use. It appears that US farmers are the main beneficiary of this scenario (their gains increase by 13.9 billion dollars), thanks to their possibility to export gly-free v&f to the Europe without paying additional taxes to reduce their overall chemical use. Logically, producers from RoW lose from the addition of mirror clauses in our setting (by 11.8 billion dollars). Overall, foreign producers gain (by 2.1 billion dollars) more than European ones. The addition of mirror clauses to the Green Deal thus supports European farm incomes without hurting other producers globally.

As expected the addition of mirror clauses increases the food bills paid by American and European households. The latter now experience higher food prices, in particular because processed foods that include gly-free v&f are more expensive. On the other hand, RoW consumers experience a small decrease of their food expenditures, compared to the Green Deal scenario, due to market effects reported above.

Discussion

Our central results just discussed are conditional to the different assumptions made. The significance of three critical assumptions are examined in additional scenarios.

On the explicit modelling of gly-free v&f technology and market

We previously argued that it is crucial to allow new technologies and markets to appear when economic conditions are favourable. We now simulate our two scenarios, assuming that the gly-free v&f technology and market do not exit. Our model thus reverts to the standard CGE model used in previous studies. We only introduce the European input tax in the Green Deal scenario. For the mirror clause scenario, we introduce in addition a similar input tax in the US (targeting a 35 per cent reduction of chemical use in conv v&f) and a prohibitive European tariff on conv v&f coming from the RoW. We thus follow Beckman et al., 2022 with only one difference: we impose a prohibitive scenario and not a speculative 50 per cent tariff.

The impacts of the Green Deal scenario are reported in Tables A.1 and A.2 and compare to Tables 1 and 2. The impacts are qualitatively the same, the main difference concerns European production of conv v&f : it now decreases by 32.9 per cent while it disappears in our central results. The second noticeable difference concerns the environmental leakage effects. The global farm chemical use increases less (0.2 per cent, compared to 0.5 per cent in the central results) because foreign production increases by less.

The impacts of the mirror clause scenario simulated with our standard CGE model are reported in Tables A3 and A4. We first analyze this scenario in isolation. Not surprisingly, we find that the imposition of the US input tax leads to a huge decrease of chemical use in the US and hence a significant decrease of US v&f production. US exports to the European market still increase considerably (by 445 per cent) because RoW producers are no longer able to export to the European market. On the other hand, we find that US exports to the RoW nearly disappear. The reduction of European v&f consumption is now considerable (by 38.6 per cent), mostly explained by the higher European price of conv v&f (73.4 per cent). The welfare impacts are also significant. We find a reduction of global chemical use (by 0.1 per cent) mostly thanks to the US input tax. The income of US producers now decreases (by 19.9 billion dollars), also due to the US input tax. Finally, the food bill of US households slightly decreases (by 0.1 per cent) due to an income effect and a higher consumption of cheaper other food products. By contrast, the food bill of European households increases considerably (by 29.1 billion dollars or by 1.5 per cent) in part due the higher prices of processed foods.

It thus appears with our standard CGE model that the addition of the mirror clause considerably improves the global environmental impacts of the Green Deal, by limiting the leakage to foreign countries. On the other hand, this addition penalizes much more foreign producers (by 18 billion dollars) than it supports the income European producers (by 3 billion dollars). According to these figures, which are consistent with those of Beckman et al. 2022, the addition of mirror clauses is more likely to be contested by foreign producers. We previously obtain the opposite result with our innovative CGE model detailing new production standards and markets. The simple reason is that it captures that a mirror clause can be effectively imposed on a production technology, and is not a taxation scheme that leads to an overall reduction in chemical use.

a. On the calibration of the gly-free v&f technology

Our empirical results are obviously conditional on the many calibrating assumptions required. We gather many figures for the European v&f sector and simply extrapolate them to foreign countries. We furthermore simplify the analysis by assuming prohibitive segregation/identity costs in the RoW. It might be the case that for some (developing) countries, their production costs of gly-free v&f, relative to conv v&f, as well as their segregation/identity costs, will be lower than those assumed above. Thus these countries may be able to produce and export gly-free v&f to the European market as well as US producers. On the other hand, these countries may offer more differentiated (tropical) products, meaning that their substitutability with European products may not be perfect. Measuring the net effect of these two dimensions is left for future research.

As regards the assumptions made for the US v&f sector, two dimensions not factored into the previous analysis can question our calibration choice. First, there is growing evidence of increasing resistance of weeds to glyphosate (Van Deynze et al., 2022), meaning that the production costs of conv v&f may increase in the future, irrespective of the Green Deal. Second, there is greater optimism in the US, compared to the EU, on the promise of biotechnology, particularly the new breeding technologies (Paarlberg, 2022). We capture these two dimensions with a sensitivity analysis of our calibration of the gly-free technology in the US. In this sensitivity analysis, we assume that the US gly-free yield is only 5 per cent lower than its conventional counterpart (it was 10 per cent in our central analysis). This alternative assumption means that the price needed to push US farmers to grown gly-free v&f is initially only 9 per cent higher than the price of conv v&f.

The market impacts of our Green Deal scenario with this alternative calibration are reported in Table B.1. They are nearly equal to the market impacts of this scenario with our central calibration. Indeed, it appears that US farmers only just start producing gly-free v&f (by 0.2 per cent of their initial v&f production). The welfare impacts of this scenario are thus roughly the same as those obtained with the central calibration.

The market impacts of the mirror clause scenario with this alternative calibration are reported in Table B.3. Here we observe noticeable quantitative differences with the results reported in Table 3. The simulated price of US gly free v&f is now 20.8 per cent higher than the initial conv v&f price (it is 26 per cent in the central calibration). The US production of gly-free v&f is greater, amounting to 62.9 per cent of initial US production (compared to 59.4 per cent). In terms of welfare (Table B.4.), the addition of the mirror clause becomes even more beneficial to US farmers (by 14.7 billion dollars, given by the difference between 17.4 and 2.7 billion dollars), compared to European producers (by 0.6 billion dollars). The higher productivity of US farmers when growing gly-free v&f benefits EU households whose food bills increase less (by 5.8 billion dollars, compared to 9.1 billion dollars in the central calibration).

On the endogenous level of the EU chemical tax

All results discussed above assume that the EU tax applied to chemical use by both v&f technologies is adjusted to ensure that chemical use decreases by 35 per cent. To assess the significance of this assumption, we perform a modified mirror clause scenario where we no longer adjust the EU input tax level (it is maintained at the 270 per cent level required in the initial Green

Deal scenario). We perform this new scenario using our central modelling framework. Results are reported in Table C3 and C4. The most obvious effect is on European chemical use by the v&f sector : it now decreases by 8.3 per cent, compared to the 35 per cent in the original mirror clause scenario. This difference clearly shows that EU member states, if they succeed in implementing mirror clauses, will need to implement strengthened additional policy instruments to reach the Green Deal environmental objectives. Still, this modified mirror clause scenario leads to a global decrease of chemical uses, compared to the Green Deal scenario (comparison of Table C4 with Table 2). We also find that this modified scenario greatly benefits European farmers (their incomes increase by 23 billion dollars, compared to the Green Deal scenario) while hurting other producers globally (by 18.3 billion dollars). More precisely, even if US producers are able to export gly-free products to the European markets, their income gain becomes small in comparison of the huge income effect on producers from the RoW. The gains of US (respectively RoW) producers reach 2.7 (resp. 33) billion dollars with the Green Deal scenario but amount to only 9 (resp. 8.4) billion dollars with the modified mirror clause scenario. These figures quantify the standard protection effects of trade measures and the fears by foreign producers that the Green Deal with mirror clauses will protect European farm incomes while hurting their incomes.

Conclusions

This paper has presented a case study of the impacts of a ban on glyphosate use in vegetable and fruit production in the EU together with a significant (35%) reduction in the use of chemical inputs in line with the objectives of the EU Green Deal strategy. These impacts are compared with and without the implementation of a mirror clause that would also prevent the import of vegetables and fruits produced using glyphosate in third countries. Previous studies of these impacts have only considered a fixed number of technologies (for example, without distinguishing between conventional production with glyphosate and glyphosate-free production). They have implemented these Green Deal objectives by imposing an input tax on the undesirable inputs which, in a mirror clause scenario, is also assumed to apply in countries wishing to export to the EU.

The Green Deal scenario leads to a substantial income loss for EU farmers, gains for third country producers, an increase in global chemical use both in fruit and vegetable production and in aggregate farm sector output (due to lower use of chemicals per unit of v&f output in the EU), and higher EU consumer bills for v&f expenditure. With the introduction of a mirror clause, the EU farm income loss is slightly diminished, global chemical use increases but not by as much, EU consumer expenditure on v&f further increases but, significantly, so does US farm income (though partly at the expense of producers in RoW), The US gain from the introduction of a mirror clause reflects the possibility to export gly-free v&f to the EU without facing additional tariffs (though with a small segregation charge) and without paying additional taxes to reduce their overall chemical use.

In conclusion, this paper provides a nuanced examination of the potential economic effects of introducing mirror clauses to complement Green Deal initiatives in the EU agricultural sector. It demonstrates that a mirror clause can partly offset potential negative impacts for EU producers from Green Deal measures as well as the risk of off-shoring environmental consequences but at the cost of higher prices for EU consumers. Significantly, the original methodology employed in this paper shows that non-EU producers are not necessarily harmed by mirror clauses but, depending on assumptions regarding the productivity of alternative technologies, may well be able to benefit.

Table 1. Market impacts of the Green Deal scenario

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to RoW	Final Demand	Price	Supply	Final Demand
USA	1.4	3.1	96.6	1.4	-0.8	9.4		
EU	-	-100	-	-100	-76.9	12.6[a]	-40.5[b]	-31.9[c]
RoW	0.9	2.6	101.3	-	-0.4			

[a]: the simulated price of gly-free v&f is 12.6 per cent higher than the initial price of conv v&f.
[b]: the simulated production of gly free v&f is 40.8 per cent lower than the initial production of conv v&f
[c]: the simulated final demand of gly-free v&f is 32.1 per cent lower than the initial final demand for conv v&f.

Table 2. Welfare impacts of the Green Deal scenario

	Chemical use in v&f (%)	Chemical use in ag sector (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	3.1	0.5	2.1 (5.9)	2.7 (1.8)	0.2 (0.4)	0.4 (0+)
EU	-35.2	-7.1	-24.0 (-48.6)	-28.9 (-13.1)	1.6 (2.4)	-0.9 (-0.1)
RoW	2.6	0.9	28.9 (3.8)	33.0 (1.7)	4.7 (0.8)	9.9 (0.2)
Total	1.5	0.5				

Table 3. Market impacts of the Mirror clause scenario

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	8.4	-45.9	-100	-73.4	-3.1	26.0	-40.6	
EU	-	-100		-100	-100	29.2	-39.7	-19.8
RoW	0.6	1.5	-100		-0.3			

Table 4. Welfare impacts of the mirror clause scenario

	Chemical use in v&f (%)	Chemical use in ag sector (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	20.2	2.5	14.9	16.6	0.8	5.5
EU	-35.0	-7.1	-23.3	-26.0	2.5	9.1
RoW	1.5	0.6	16.7	21.2	3.1	8.4
Total	1.1	0.4				

Table A.1. Market impacts of the Green Deal scenario: with the standard CGE model

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	0.9	2.1	64.7	0.7	-0.5			
EU	7.7	-32.9	-	-76.5	-3.3			
RoW	0.6	1.8	69.9	-	-0.3			

Table A.2. Welfare impacts of the Green Deal scenario: with the standard CGE model

	Chemical use in v&f (%)	Chemical use in farms (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	2.1	0.4	1.5	1.8	0.1	0.2
EU	-35.0	-7.1	-23.3	-26.0	0.9	-1.0
RoW	1.8	0.7	20.2	22.9	3.2	6.8
Total	0.7	0.2				

Table A.3. Market impacts of the mirror clause scenario: with the standard CGE model

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	11.2	-32.7	445.7	-95.8	-4.4			
EU	73.4	-30.4		-100	-38.6			
RoW	0.8	2.3	-100		-0.4			

Table A.4. Welfare impacts of the mirror clause scenario: with the standard CGE model

	Chemical use in v&f (%)	Chemical use in ag sector (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	-35.0	-4.2	-18.3	-19.9	0.8	-0.1
EU	-35.0	-7.8	-20.8	-23.0	-0.9	29.6
RoW	2.3	0.7	24.7	26.5	4.4	10.0
Total	-0.3	-0.1				

Table B.1. Market impacts of the Green Deal scenario: alternative calibration

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	1.4	3.0	96.2	1.2	-0.8	9.4	-99.8	
EU	-	-100	-	-100	-77.0	12.6	-40.5	-31.7
RoW	0.9	2.6	100.9	-	-0.4			

Table B.2. Welfare impacts of the Green Deal scenario: alternative calibration

	Chemical use in v&f (%)	Chemical use in ag sector (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	3.1	0.5	2.2	2.7	0.2	0.4
EU	-35.0	-7.0	-24.1	-26.9	1.6	-0.9
RoW	2.6	0.9	28.4	33.0	4.7	9.9
Total	1.5	0.5				

Table B.3. Market impacts of the mirror clause scenario: alternative calibration

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	8.2	-45.1	-100	-72.2	-3.0	20.8	-37.1	
EU	-	-100		-100	-100	23.5	-40.0	-16.4
RoW	0.5	1.4	-100		-0.3			

Table B.4. Welfare impacts of the mirror clause scenario: alternative calibration

	Chemical use in v&f (%)	Chemical use in farms (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	21.2	2.6	15.7	17.4	0.8	5.6
EU	-35.0	-7.1	-23.6	-26.3	2.2	5.8
RoW	1.4	0.6	16.3	20.5	3.0	7.8
Total	1.1	0.4				

Table C3. Market impacts of the modified mirror clause scenario

	Conv v&f (changes in %)					Gly free v&f (% of initial conv v&f)		
	Price	Supply	Exports to EU	Exports to Row	Final Demand	Price	Supply	Final Demand
USA	4.8	-28.8	-100	-47.6	-1.9	21.5	-63.9	
EU	-	-100		-100	-100	24.8	-16.3	-17.0
RoW	0.2	0.5	-100		-0.1			

Table C4. Welfare impacts of the modified mirror clause scenario

	Chemical use in v&f (%)	Chemical use in ag sector (%)	v&f income ($bn and %)	Farm income ($bn and %)	v&f bill ($bn and %)	Food bill ($bn and %)
USA	11.4	1.4	8.1	9.0	0.5	3.4
EU	-8.3	-1.8	-5.4	-5.9	2.5	10.8
RoW	0.5	0.3	5.9	8.4	1.4	4.2
Total	0.7	0.2				

References

Baldon, C., S. Beaussant, M. Colli, B. Buczinski, S. Leré, and S. Lickel. 2021. *How Can We Stop the Import of Food Produced Using Banned Practices in Europe? A European Regulation to Protect the Environment and Our Farmers*. Paris: Fondation Nicholas Hulot pour la nature et l'homme, Institute Veblen and Interbev.

Bareille, F., and A. Gohin. 2020. "Simulating the Market and Environmental Impacts of French Pesticide Policies: A Macroeconomic Assessment." *Annals of Economics and Statistics*, no. 139: 1–28. https://doi.org/10.15609/annaeconstat2009.139.0001.

Barreiro-Hurle, J., M. Bogonos, M. Himics, J. Hristov, I. Pérez-Domínguez, A. Sahoo, G. Salputra, F. Weiss, E. Baldoni, and C. Elleby. 2021. "Modelling Transitions to Sustainable Food Systems: Are We Missing the Point?" *EuroChoices* 20 (3): 12–20. https://doi.org/10.1111/1746-692X.12339.

Beckman J., Burfisher M., Mitchell L., Arita S. 2021. Hidden obstacles to trade: The case of the EU's Ban on beef hormones. *Journal of Policy Modelling*, 43: 1332-1343

Beckman J., Ivanic M., Jelliffe J., Arita S. 2022. Adopt or not adopt? Mirror clauses and the European Green Deal. *Applied Economic Perspectives and Policy,* 44: 2014-2033

Carpentier, A, and E. Letort. 2014. "Multicrop Production Models with Multinomial Logit Acreage Shares." *Environmental and Resource Economics* 59 (4): 537–59. https://doi.org/10.1007/s10640-013-9748-6.

Drouillard J.S. 2018. Current situation and future trends for beef production in the United States of America. A Review. *Asian-Australas J Anim Sci*, 31(7):1007-1016

European Commission. 2021. *Trade Policy Review - An Open, Sustainable and Assertive Trade Policy*. COM(2021) 66. Brussels.

———. 2022. *Application of EU Health and Environmental Standards to Imported Agricultural and Agri-Food Products*. Brussels.

Matthews, A. 2022. *Implications of the European Green Deal for Agri-Food Trade with Developing Countries*. Brussels: European Landowners' Organisation.

Paarlberg R. 2022. The trans-Atlantic confilt over "green" farming. *Food Policy,* 108.

Van Deynze B., Swinton S.M., Hennessy D.A. 2022. Are glyphosate resistant weeds a threat to conversvation agriculture? Evidence from tillage practices in soybeans. *American Journal of Agricultural Economics,* 104: 645-672

Wesseler, J. 2022. "The EU's Farm-to-Fork Strategy: An Assessment from the Perspective of Agricultural Economics." *Applied Economic Perspectives and Policy*. https://doi.org/10.1002/aepp.13239.

Adding mirror clauses within the European Green Deal: Hype or hope?

Supplementary Information

Modelling framework

Our starting modelling framework is the widely used GTAP framework to assess the ex ante market and welfare effects of many policy scenarios (such as trade, environmental, climate, agriculture, climate, fiscal policies). Like Beckman et al. (2021, 2022), we elaborate on the static version, assuming perfect competition in all markets, that producers maximize their profits subject to market and technological constraints, and that households maximise their utility subject to budget constraints. We adopt a medium term horizon, assuming that physical capital is fixed in each sector while other primary factors (whose total supply are fixed) are perfectly mobile across sectors.[5]

We implement this CGE model using the GTAP10A database, which gathers economic flows of the 2014 year. We aggregate the 141 regions in that database in 3 regions only (the EU, US and Rest of the World), which is the maximal aggregation level allowing us to quantify the potential contrasting impacts of mirror clauses while requiring the minimal amount of external data on new standards. We aggregate the 65 sectors/products as Beckman et al. and accordingly only consider

[5] As regards the macroeconomic closures, we assume that per region government expenditures are exogenous, total investment and net capital account per region are fixed (consistently with the assumption of fixed capital in each sector), so that private savings adjust to ensure macroeconomic equilibrium. These assumptions have negligible consequences on the results reported in this paper (Kilkenny and Robinson, 1990).

the aggregate of v&f.[6] Importantly the GTAP database includes an aggregate "chemical" sector that does not differentiate mineral fertilizers, pesticides and antimicrobials. It means that this database does not provide the amounts of nitrogen or glyphosate or other pesticides that are used in a particular crop activity in a particular region, as these data are not publicly collected in any region. Still some previous authors examine the contribution of glyphosate to agriculture using this framework (Brookes et al., 2017) and we will partly follow their example.

1. Supply modelling

1.1 Issues with the standard approach

The standard approach of crop supply modelling in CGE models is to assume the existence of an aggregate mono-product technology, usually specified with nested Constant Elasticity of Substitution (CES) functions. The choice of substitution elasticities between pairs of inputs is obviously crucial, as it governs the price responses of crop supply. This aggregate approach may seem at odds with the diversity of crop management practices that farmers may implement on their farms, which diversity is generally captured in individual farm microeconomic models. However, the economic consistency of the aggregate approach was theoretically demonstrated more than half a century ago. Houthakker (1955), then followed by Levhari (1968) and Sato (1969),

[6] Chepeliev et al. (2021) develop a supplemental database where the v&f commodity is disaggregated in 79 commodities. The production technology and cost of these commodities are not available, preventing us to analyze the effects of new standards on particular v&f.

demonstrate that a CES function at the national level is fully compatible with fixed technologies at the field level. The condition is that one production factor is heterogeneous. This idea has been investigated in the agricultural economic literature. For instance, Hertel *et al.* (1996) show that the aggregate substitution elasticity between land and fertilizer can be significant, even if it is limited at the field level, with soils and climate being heterogeneous factors.

Accordingly, this aggregate approach is consistent with the existence of farmers applying different production techniques given their particular (soil/climate) conditions. It captures that some farmers use significant/no amount of a controversial active substance and that they switch from one crop management practice to another one depending on price incentives. On the other hand, this aggregate approach does not fully recognize the potential different qualities of the delivered crop products because they are sold at the same price on domestic/foreign markets. This price is usually an average of the market prices of the different crop qualities. The implicit assumption is that the price differences across these qualities (for instance, between organic and conventional crops) do not change with the contemplated policy scenario. This assumption is unlikely in our case study of a new standard leading to a new product, whose price is initially unknown. We underline that a glyphosate-free v&f is not an organic one, in particular as we do not prohibit the use of other synthetic pesticides or mineral fertilizers.

1.2 Our approach

We thus need to develop a more detailed crop supply modelling to account for new production standards delivering new differentiated products. We develop a new specification, inspired by the structural microeconomic approach of Carpentier and Letort (2014). It has already been partly implemented in a reduced form manner in the Global Change Analysis Model (GCAM) PE model

(Sands et Leimbach, 2003).and in structural form manner by Bareille and Gohin (2020) in their CGE model, but assuming that the numbers of commodities and technologies are fixed. We extend it to allow for latent production standards and commodity markets, using virtual prices. Below we explain it focusing on the v&f sector, even if it can be implemented for any sector.

We specify a multi-output, multi-input technology for the v&f sector in each country. In the application, we consider only two outputs or activities, hereafter named conventional v&f (short name is conv v&f) and glyphosate-free v&f (short name is gly-free v&f). The first is initially produced in positive quantities while the production of second is initially null in all countries. Two inputs (chemicals and a composite factor used for mechanical weeding) are assumed allocable while other inputs are not. These non allocable inputs are combined (with a standard structure of nested CES functions) by an assembly subprocess to produce an assembly output that is used as intermediate inputs by our two activities. This kind of separability assumption has already been specified in CGE models (Peterson et al., 1994), capturing that some (mixed) farms offer many products and some inputs are specific to some activities. For instance, a single farm may produce both conventional and organic products using the same accounting services or the same farm machines (Peterson et al. consider labor, buildings and non-feed inputs that can be used in many livestock operations).

The originality of our crop supply modelling lies in the specification of the functional forms that govern the substitution pattern between allocable inputs at the activity level and the allocation of the assembly output between the two activities. More precisely, we first specify a flexible quadratic yield function for each v&f activity (while this is a leontief function in Sands and Leimer). Yield per hectare depends on the application of chemicals and mechanical weeding factors per hectare. Maximizing the margin per hectare leads to optimal chemical input use, mechanical weeding, yields and returns per hectare for both activities. Formally, we solve the following programs:

$$\pi_j = max_{x_j,y_j}\ p_j.y_j - w'.x_j$$

Subject to: $y_j = a_j - 0.5.\left(b_j - x_j\right)'\nabla_j^{-1}\left(b_j - x_j\right)$

With p_j the price of the output offered by the activity j, y_j the yield per hectare, w the vector of input prices, x_j the vector of input use per hectare, a_j, b_j, ∇_j the deep parameters of the yield function. Optimal input use, yield and return per hectare are given by:

$$x_j = b_j - \mathrm{p}_j^{-1}\nabla_j w \quad (1)$$

$$y_j = a_j - 0.5.p_j^{-2}w'\nabla_j w \quad (2)$$

$$\pi_j = p_j a_j - w'b_j + 0.5.p_j^{-1}w'\nabla_j w \quad (3)$$

These functions satisfy the usual properties, in terms of curvature and homogeneity, if ∇_j is a positive semidefinite matrix. One important property of this specification is the possibility to rely on agronomic functions to calibrate the deep parameters (Femenia and Letort, 2016). This is obviously important in our case where the glyphosate-free technology is not yet implemented by farmers.[7]

Second, we determine the amount of the assembly output (that incorporates land) allocated to each v&f activity by maximizing the total return (sum of returns per hectare times the optimal acreage) minus an entropic cost function and total land allocated to the v&f sector. This cost function implicitly captures the different reasons why v&f farmers (at the individual level or at the aggregate level) do not fully specialize in the most profitable activity (for example due to dynamic agronomic constraints, management of labor peak loads, risk management, heterogeneity of land qualities). Formally, the optimal v&f acreages solve the following program in each region:

$$max_{s_j \geq 0} \ \sum_j \pi_j . s_j - \sum_j c_j . s_j - \frac{1}{\alpha} \sum_j s_j . ln(s_j)$$

Subject to $\sum_j s_j = s_{v\&f}$, j=conv v&f, gly-free v&f

With s_j the acreage devoted to activity j, π_j the return per hectare for activity j determined in the first step, $s_{v\&f}$ the total land devoted to veg&fruit production, c_j and α the deep parameters of the entropic cost function. The optimal acreage devoted to each activity is then given by:

$$s_j = s_{v\&f} . \frac{e^{\alpha(\pi_j + \mu_j - c_j)}}{\sum_{j'} e^{\alpha(\pi_{j'} + \mu_{j'} - c_{j'})}} \qquad (4)$$

[7] We again underline that our new technology is different from an organic one, as we do not prohibit other chemical inputs. Also, even if some farmers currently may avoid the use of glyphosate in some years, they always have the possibility to use it if they encounter weeding issues.

With μ_j the endogenous lagrangian multipliers associated with the non-negativity conditions. As explained by Carpentier and Letort (2014), this specification is widely used in microeconometric analyses (with the log ratio of acreages being linear in returns). The deep parameter α is crucial as it controls the price responses of acreage. If it tends to zero, then acreage is fixed, with farmers always cropping the same amount of land. The c_j parameters of the entropic cost function have no real economic interpretation but ensure perfect calibration at the initial point.

These optimal acreages also serve to determine the amount of the assembly output allocated to each sector and its total amount (the price is implicitly given by the zero profit condition of the assembly sector and the standard nested structure of CES function between the non allocable inputs):

$$IC_{\text{asse},j}.P_{\text{asse}} = \pi_j.s_j \tag{5}$$

$$\sum_j IC_{\text{asse},j} = Q_{\text{asse}} \tag{6}$$

With $IC_{\text{asse},j}$ the intermediate consumption of the assembly output by the activity j, P_{asse} the price of the assembly output and Q_{asse} the total amount of the assembly output. All these equations ensure that profits are distributed to primary factors of production.

Our multi-production technological specification allows activities/commodities to appear or disappear according to economic incentives. This is a generalization over CGE models specifying multi-product technologies with usual functional forms, the prominent one being the Constant Elasticity of Transformation (CET). In that alternative approach, the number of active activities is exogenously controlled by the modeler (by changing the distribution parameters of the CET function). Our approach also preserves the physical land area (see Zhao et al., 2020) while taking into account the economic incentives to change the productive capacity of land (captured in our static approach with the substitution elasticity between land and other non allocable inputs).

1.3 Calibration

The implementation of our original v&f supply modelling (equations 1 to 6) requires the calibration of the deep parameters of the yield functions and of the entropic cost function. The usual practice in CGE modelling is to combine initial economic data (gathered in a social accounting matrix) with external supply price elasticities to calibrate the technology parameters of an active technology. One first challenge with this procedure is that such elasticities are often computed for main farm products/sectors, few are available for the v&f products/activities. One second challenge with this procedure is the unknown external validity of these elasticities, when they are available. They are usually econometrically estimated with past data where prices and quantities did not significantly change during a long period (see for instance Guyomard et al. 2020 on the stability of pesticide and nitrogen use in EU farming sectors). A third challenge is that initial data are not always sufficiently detailed. For our case study, the GTAP database does not distinguish the composite factor used for mechanical weeding, only the total labor and capital used by the conv v&f. To cope with the last challenge, we will only introduce the additional composite factor used for mechanical weeding required for the gly-free v&f technology, which is information available in the economic literature. To cope with the elasticity issue, we rely on the survey conducted by Bremmer et al. (2021). These authors ask agronomic experts about the yield effects of reducing fertilizers and pesticides (without distinguishing the different pesticides) for different crops. For apples, tomatoes and grapes, they report yield reductions between 14 and 20 per cent when reducing mineral fertilizers by 20 per cent and between 10 and 20 per cent when reducing pesticides by 50 per cent. They also indicate that there are no significant interactions between these effects. We thus calibrate the parameters of the European yield functions of the conv v&f using the initial economic data of the GTAP database (on conv v&f production, acreage, yield and chemical use) and the following "agronomic" point. A 35 per cent reduction of chemical use (a simple average of the 20 per cent and 50 per cent reduction of fertilizers and pesticides) leads to a 35 per cent reduction of conv v&f yield.

Formally, we only have three parameters in each region (a_j, b_j, ∇_j) because we have an aggregate input. We compute them with the three following equations:

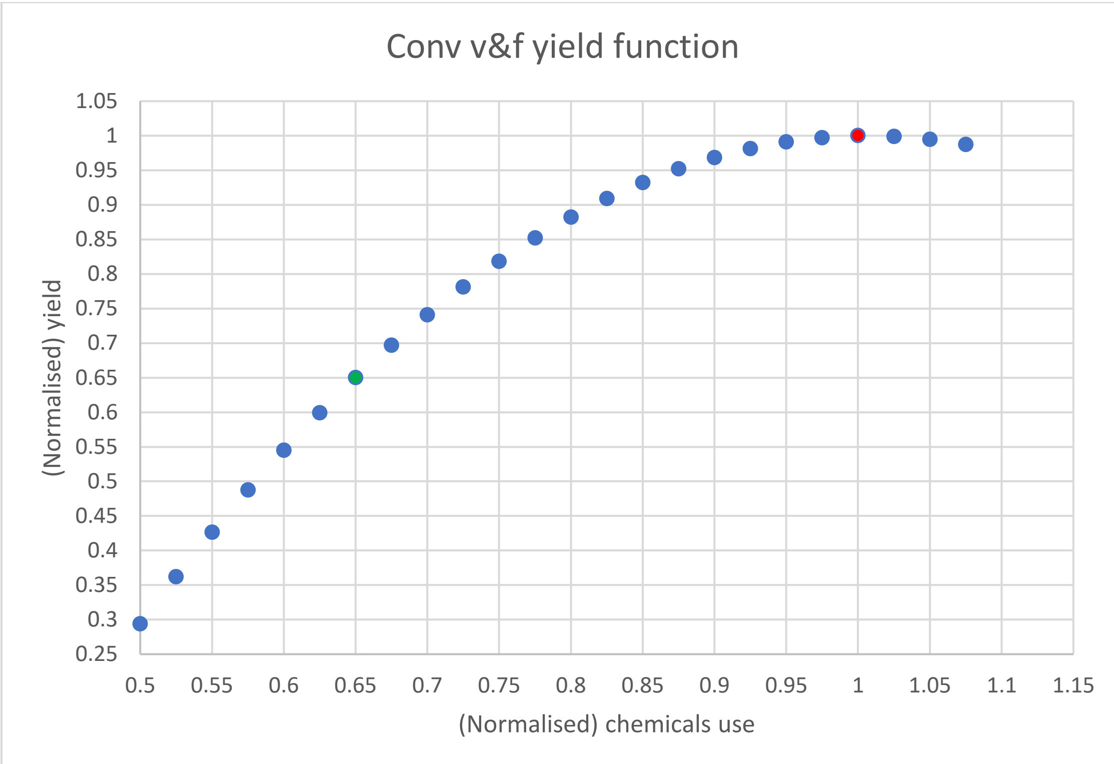
$$y_j^0 = a_j - 0.5.\left(b_j - x_j^0\right)' \nabla_j^{-1}\left(b_j - x_j^0\right) \quad (7)$$

$$x_j^0 = b_j - \nabla_j w^0 / p_j^0 \quad (8)$$

$$y_j^1 = a_j - 0.5.\left(b_j - x_j^1\right)' \nabla_j^{-1}\left(b_j - x_j^1\right) \quad (9)$$

The first two equations are defined at the initial point (with the superscript 0). The third one is defined at the "primal" point given by experts (with the superscript 1).

Figure A1 reports our calibrated conv v&f yield function (the vertical axis), depending on the use of chemicals (the horizontal axis). For this figure, we normalise quantities to one. The initial point is given by the red point and the "primal" point by the green point. One can see that our calibrated yield function is not linear. For instance, a 20 (respectively 50) per cent reduction of chemical use leads to a 12 (respectively 70) per cent of yield. On the other hand, we obtain that a slight increase of the use of chemicals reduce yields, hence the marginal productivity becomes negative beyond the initial point.



This figure shows that our calibrated production function is different from a linear, input-output, function. At the initial point, the price elasticity of yield is close to zero (0.001) but quickly become significant: this price elasticity reaches one at the agronomic point. We proceed similarly for the other regions, again assuming this relationship. To our knowledge, this calibration procedure with external field data is unusual but consistent with the econometric approach developed by Rosas et al. (2019). These authors show significant effects on their econometric estimates of crop yield responses to prices when experimental data are combined with market data.

As regards the calibration of the parameters of the yield function of the gly-free v&f technology, an expanding literature on arable crops assesses the impacts on yields, other herbicide uses and additional weeding costs of a glyphosate ban (Bocker et al., 2020, Ye et al., 2021). The literature is less developed on v&f crops. According to Jacquet et al. (2019; 2021), a glyphosate ban may induce a yield decrease between 5 and 40 per cent for French apple and plum trees while having negligible impacts on French vineyard productivity. Jacquet et al. also compute the additional mechanical weeding costs, assuming that the glyphosate ban does not lead to additional use of other (more expensive) herbicides. These additional costs represent on average 2.6 per cent of current revenue, with great diversity across time, French regions and v&f commodities. We combine these information sources as follows. First we assume that the gly free v&f yield response to chemical inputs is the same as the conv v&f technology (this is captured by assuming the same ∇_j parameters). This first assumption implies for instance, that reducing mineral fertilisers has the same yield impact on gly free and conv v&f. Second we assume that for the same values of aggregate chemical use, the gly-free yield is 10 per cent lower than the conv v&f yield (we capture this by decreasing the a_j parameter by 10 per cent while not changing the b_j parameter). This second assumption intends to reflect that other herbicides are less efficient than glyphosate in the control of weeds. Third, we assume that the gly-free v&f technology requires more labor time, without any substitution between this additional labor and chemicals. We calibrate the relevant input output coefficient to 3 per cent. This third assumption intends to capture the additional non-chemical costs of alternatives to the systemic glyphosate (either in mechanical weeding control or more time to apply other selective herbicides). Again, we proceed similarly for the other regions, assuming the same figures. The only difference concerns the segregation/identity costs that will appear in our simulations. A European glyphosate ban implies that European producers do not need to identify their v&f products while foreign producers need to do so if some of them want to export their products to the European markets. We assume that these additional segregation/identity costs are paid by producers and amount to 1 per cent of current output values for US producers (based on the small amounts reported in Beckman et al., 2021). We simplify the analysis by assuming that other countries have prohibitive segregation/identity costs, an assumption that can be explored in further research.

As regards the calibration of the parameters of the entropic cost function, we also need external information, such as the amount of land that can be converted into gly-free technology as a function of returns per hectare. Jacquet et al. (2021) find that the additional costs due to a glyphosate ban on French vineyards range from 0.3 to 4.4 per cent of current output values, with an average value of 2.6 per cent. Accordingly our calibration procedure targets a 5 per cent difference between i/ the virtual price of the gly-free v&f that leads first farmers to adopt the gly-free technology and ii/ the virtual price of the gly-free v&f that leads all farmers to abandon glyphosate. To be consistent with the above assumption of a 10 per cent decrease of the gly-free v&f yield, we assume that the first virtual price is 13 per cent higher than the current price of the conv v&f and the second virtual price is 18 per cent higher than the current price of v&f. With these two points and a normalization rule, we are then able to calibrate all parameters of the entropic cost function.

Again, for each region, we have three parameters: $c_j, j = conv, gly - free$ and α. Initially the acreage devoted to gly-free technology is zero and becomes positive when the price of gly-free is 13 per cent higher than the price of conv v&f. For the calibration, we assume that the share of acreage devoted to gly-free v&f is 1 per cent at this first unobserved point (with the subscript 0). The ratio of acreage is thus given by:

$$\frac{s^0_{gly-free}}{s^0_{conv}} = \frac{0.01}{0.99} = \frac{e^{\alpha\left(\pi^0_{gly-free} - c_{gly-free}\right)}}{e^{\alpha\left(\pi^0_{conv} - c_{conv}\right)}} \quad (10)$$

We next assume that the share of acreage devoted to gly-free v&f is 99 per cent when the price of gly-free v&f is 18 per cent higher than the price of conv v&f. At this second unobserved point (with the subscript 1), the ratio of acreage is given by:

$$\frac{s^1_{gly-free}}{s^1_{conv}} = \frac{0.99}{0.01} = \frac{e^{\alpha\left(\pi^1_{gly-free} - c_{gly-free}\right)}}{e^{\alpha\left(\pi^0_{conv} - c_{conv}\right)}} \quad (11)$$

This second ratio is again independent of the total acreage devoted to v&f, which may depend on the total profits generated by the two v&f technologies. Dividing (10) by (11) directly gives the α parameter:

$$\alpha = \frac{log\left(\frac{0.01*0.01}{0.99*0.99}\right)}{\pi^0_{gly-free} - \pi^1_{gly-free}} \quad (12)$$

As regards the linear parameters c_j, they are not fully identified (cf Carpentier and Letort, 2014). We assume that at the first unobserved point, they ensure that the denominator of the acreage equation equals one:

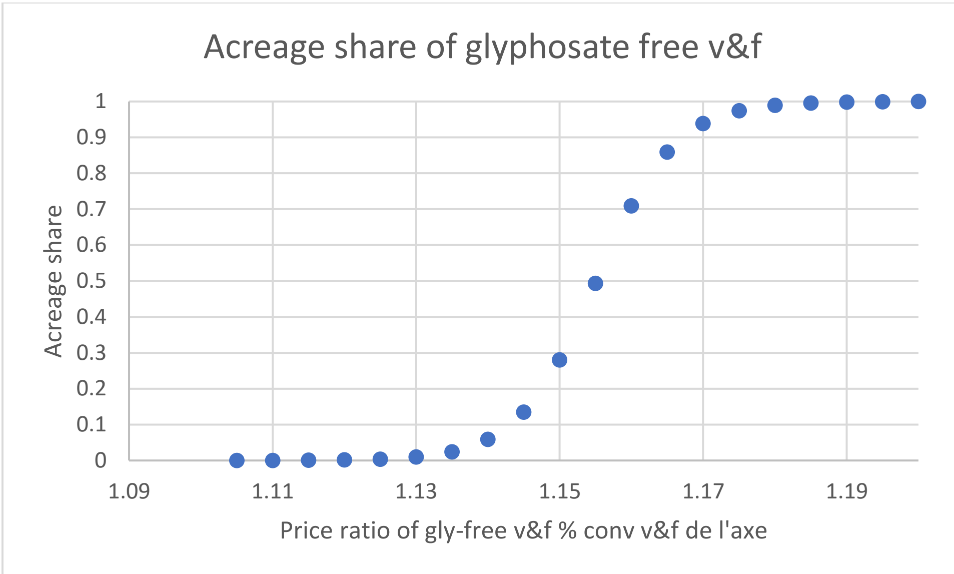
$$e^{\alpha\left(\pi^0_{gly-free} - c_{gly-free}\right)} + e^{\alpha\left(\pi^0_{conv} - c_{conv}\right)} = 1$$

Then we have:

$$c_{gly-free} = \pi^0_{gly-free} - \log{(0.01)}/\alpha$$

$$c_{conv} = \pi^0_{conv} - \log{(0.99)}/\alpha$$

Figure A2 reports the evolution of optimal acreage share devoted to gly-free technology with respect to the price of this product. As expected, this share is null for price ratio lower than 1.13 and this share is one for price ratio higher than 1.18. When this price ratio reaches 1.15, then our calibration implies that 30 per cent of farmers (or 30 per cent of their acreage) is cropped without glyphosate.



Our calibration approach shares similarities with Brookes et al. (2017) who assess the combined contribution of glyphosate to agriculture and GM crops (Bt corn). Like these authors, we introduce farm level impacts as productivity shocks to our CGE model. But we have one major difference in that we allow coexistence of conventional and glyphosate free technologies in non EU regions. On the other hand, Brookes et al. ban glyphosate and Bt corn globally.

2. Demand modelling

2.1 Issues with the standard approach

The GTAP model distinguishes five types of demand for each commodity: i/ intermediate demands by domestic firms, ii/ demands by public institutions, iii/ final demand by households, iv/ stock variation and v/ import demands by foreign agents. These different demands are usually specified using nested homothetic CES functions (eventually with zero substitution elasticities), the exception being for the final demand with potentially more flexible non-homothetic forms (such as the Constant Difference of Elasticity). These specifications are globally regular and contribute to the existence of a unique general equilibrium. But they are only partially flexible in their price/expansion/income effects. More importantly, these specifications do not allow initial latent demands to become effective depending on economic conditions. They do not allow as well initial existing demands to disappear. For our case study, it means that the European final demand of conv v&f will never disappear, even if the price of conv v&f reaches high level. It also implies that a potential demand for gly-free v&f does not exist.

This "zero" issue is a long lasting issue in trade policy analysis (Romer, 1994). The predominant CES modelling of trade flows, also called the standard Armington approach reflecting national product differentiation, has long been criticized for prohibiting new trade flows and leading to high terms of trade effects of trade policy scenarios (Brown, 1987). Three main solutions have been implemented so far to solve this issue. The first consists in the exogenous modification of the parameters of the CES function in the CGE model (Philippidis et al., 2014). This solution implicitly assumes a change of preferences by households (over domestic/foreign goods), at least making difficult welfare analysis. The second consists in removing the product differentiation assumption captured with the CES and replacing it by the specification of non linear transport costs (Mosnier, 2014). This second solution critically depends on the calibration of these non linear transport costs (Jansson and Heckelei, 2009). The third solution consists in specifying more flexible functions. This has already been implemented by Witzke et al. (2005) and Gohin and Laborde (2006). Witzke et al. (2005) replace the CES function with a Linear Expenditure System (LES) with negative commitments. This approach is not fully flexible in price effects. Gohin and Laborde (2006) instead implement the Normalised Quadratic Expenditure System (NQES) which is flexible and globally regular when virtual prices are introduced to deal with zero trade flows. We follow this approach.

2.2 Our approach

We specify a NQES at the import demand side, permitting European imports of conv v&f to cease if a glyphosate ban coupled with a mirror clause is implemented. We also implement this NQES at the final demand side, permitting households to start consuming gly-free v&f when economic conditions are favorable. As regards intermediate demands of v&f by processing firms, we assume a perfect substitutability between the two v&f while other demands (stock variation and governmental demands) are fixed.

We formally present below the NQES as applied to the final demand side in one region. The same type of equations apply at the import demand side, by replacing utility by commodity demand. This NQES is given by:

$$E(P,U) = A(P^d) + B(P^d).U \quad (13)$$

With $A(P^d) = \sum_i \alpha_i . P_i^d$ and $B(P^d) = \sum_i \beta_i . P_i^d + 0.5.\frac{\sum_i \sum_j \gamma_{ij}.P_i^d P_j^d}{\sum_i \delta_i . P_i^d}$

Where U stand for the utility, P^d the vector of prices at the demand level $\alpha, \beta, \gamma, \delta$ the deep parameters to be calibrated. From the Shephard lemma, we obtain the hicksian demand functions:

$$D_i = \alpha_i + U.\left(\beta_i + \frac{\sum_j \gamma_{ij}.P_j^d}{\sum_l \delta_l . P_l^d} - 0.5.\delta_i.\frac{\sum_l \sum_j \gamma_{lj}.P_l^d P_j^d}{\left(\sum_l \delta_l . P_l^d\right)^2}\right) \quad (14)$$

The marshallian demand functions are simply obtained by substituting the utility level with equation (13) and the macroeconomic identity between household expenditure and income (R):

$$E(P^d, U) = R \quad (15)$$

We constrain these demands to be non negative by allowing demand prices to be different from market prices. The complementarity conditions are given by:

$$D_i \geq 0 \;\perp\; P_i - P_i^d \geq 0 \qquad (16)$$

This specification allows demand to be zero, at the initial point or after the simulation, if the market/producer price is higher than the price that households are ready to pay. This is the case in our initial situation, where the gly-free v&f product does not exist because its cost of production is higher than the virtual price of all households.

2.3 Calibration

By being more flexible than the traditional functions, the calibration of the parameters of the NQES allows to capture more external information, on price/substitution/income elasticities (we follow the calibration procedure detailed in Ryan and Wales, 1999). At the trade side, Fontagné et al. (2022) report a unique CES Armington econometric elasticity of 7 for conv v&f, but assuming that all households from developed/developing countries exhibit the same preferences. This assumption is generally not supported by country specific studies, leading to biased simulated results (Olekseyuk et Schürenberg-Frosch, 2016). Moreover European and USA v&f products are very likely more similar (mostly non tropical v&f products) than with v&f from RoW. Accordingly we double this substitution elasticity between the European/USA pair. The relevance of this elasticity will be later explored when analyzing our regional simulated price effects.

As regards the currently non produced/consumed and traded gly-free v&f, we simplify the analysis by assuming perfect substitution across sources but impose unitary transport costs. We assume that these transport costs are the same for conv and gly-free v&f while segregation/identity costs are paid by foreign producers (see above).

As regards the calibration of the NQES parameters for the final demands, we first impose some natural separability assumptions. At the upper level (with the NQES), we retain four products: the gly-free v&f, the conv v&f, an aggregate of other food products, an aggregate of other goods and services. For the two aggregates, we specify simple Cobb Douglas aggregators without prejudice, as our simulation experiments do not lead to huge price effects on other goods or income effects. For the upper level NQES parameters, a significant literature already assesses the willingness to pay by consumers for reduced exposure to pesticides. Florax et al. (2005) show that this willingness depends on the risk levels of pesticide but that the income elasticity of reduced pesticide risk exposure is generally not significantly different from zero. We thus adopt the same income elasticity for the conv v&f and gly-free consumption, using the results of the meta-analysis by Femenia (2019), indicating a 0.6 income elasticity for v&f and 0.5 for the aggregate of other food products. As regards the virtual price that leads households to start consuming gly-free v&f, we assume that it is 6.5 per cent higher than (respectively equal to) the price of the conv v&f for European (respectively non European) households. We base this assumption on Marette et al. (2021) who find that European citizens are more concerned about the human/environmental effects of new crop technologies than non European ones. We justify the 6.5 figure as being half of the increase of price that leads European farmers to start producing gly-free v&f (see above). A sensitivity analysis of our results on this guesstimated figure will be performed. Finally, we have six free cross price effects in our four good system (six free γ parameters). We first impose no cross price effects between our two v&f products and the aggregate of other goods and the same cross price effect of our two v&f products on the consumption of the food aggregate. This cross price effect is calibrated such as to reproduce the -0.6 own price elasticity of conv v&f demand reported by Femenia. Similarly the cross price effect of the food aggregate on the consumption of the other good aggregate is determined such that the own price elasticity of the food aggregate consumption equals -0.5. The last parameter to be determined governs the substitution between the conv and gly-free v&f. We calibrate it assuming that if the demand price of gly v&f reaches the demand price of conv v&f, then all European households will no longer consumer conv v&f.

References

Bareille F., Gohin A. (2020). Simulating the Market and Environmental Impacts of French Pesticide Policies: A Macroeconomic Assessment. *Annals of Economics and Statistics*, 139:1-28

Beckman J., Burfisher M., Mitchell L., Arita S. (2021). Hidden obstacles to trade: The case of the EU's Ban on beef hormones. *Journal of Policy Modelling*, 43: 1332-1343

Beckman J., Ivanic M., Jelliffe J., Arita S. (2022). Adopt or not adopt? Mirror clauses and the European Green Deal. *Applied Economic Perspectives and Policy*

Böcker T., Britz W., Möhring N., Finger R. (2020). An economic and environmental assessment of a glyphosate ban for the example of maize production. *European Review of Agricultural Economics*, 47(2): 371-402

Bremmer J., Gonzalez-Martinez., Jongeneel R., Huiting H., Stokkers R. (2021). Impact Assessment of EC 2030 Green Deal Targets for Sustainable Crop Production. Wageningen Economic Research 2021-150

Brookes G., Taheripour F., Tyner W.E. (2017). The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level. *GM Crops and Food*, 8: 216-228

Brown D.S. (1987). Tariffs, the terms of trade, and national product differentiation. *Journal of Policy Modeling*, 9, 503-526.

Carpentier, A., and Letort, E. (2014). Multicrop production models with Multinomial Logit acreage shares. *Environmental and Resource Economics 59*, 537–559

Femenia F. (2019). A meta-analysis of the price and income elasticities of food demand. *German Journal of Agricultural Economics*, 68(2): 77-98

Fontagné L., Guimbard H., Orefice G. (2022). Tariff-Based Product Level Trade Elasticities. *Journal of International Economics*.

Florax R., Travisi C., Nijkamp P. (2005). A meta-analysis of the willingness to pay for reductions in pesticide risk exposure. *European Review of Agricultural Economics*, 32(4): 441-467

Gohin A., Laborde D. (2006). Simulating trade policy reforms at the detailed level: some practical solutions GTAP conference, www.gtap.org

Guyomard, H., Bureau J.-C. et al. (2020), Research for AGRI Committee – The Green Deal and the CAP: policy implications to adapt farming practices and to preserve the EU’s natural resources. European Parliament, Policy Department for Structural and Cohesion Policies

Hertel T.W., Stiegert K., Vroomen H. (1996). Nitrogen-land substitution in corn production: a reconciliation of aggregate and firm-level evidence. *American Journal of Agricultural Economics*, 78(1): 30-40

Houthakker, H. S. (1955). The Pareto distribution and the Cobb-Douglas production function in activity analysis. *The Review of Economic Studies*, 23(1): 27-31.

Jacquet F., Delame N., Thoueille A., Reboud X., Huyghe C. (2019). Alternatives au glyphosate en arboriculture : Evaluation économique des pratiques de désherbage. https://www.inrae.fr/sites/default/files/pdf/ArboGlypho29%20decVF%20%28002%29.pdf

Jacquet F., Delame N., Lozano Vita J., Huyghe C., Reboud X. (2021). The microeconomic impacts of a ban on glyphosate and its replacement with mechanical weeding in French vineyards. *Crop protection*, 150

Jansson T., Heckelei T. (2009). A new estimator for trade costs and its small sample properties. *Economic Modelling*, 26(2): 489-498

Levhari, D. (1968). A note on Houthakker's aggregate production function in a multifirm industry. *Econometrica: Journal of the Econometric Society*, 36(1): 151-154.

Marette S., Beghin J., Disdier A.C., Mojduska E. (2021). Can foods produced with new plant engineering techniques succeed in the marketplace? A case study of apples. *Applied Economic Policy and Perspectives.*

Mosnier A. (2014). Tracking indirect effects of climate change mitigation and adaptation strategies in agriculture and land use change with a bottom-up global partial equilibrium model. PhD degree in Economic and Social Sciences at the University of Natural Resources and Applied LifeSciences (BOKU).

Olekseyuk Z., Schurenberg-Frosch H. (2016). Are Armington elasticities different across countries and sectors? A European study. *Economic Modelling*, 55: 328-342

Peterson E.B., Hertel T.W., Preckel P.V. (1994). A general equilibrium framework for the food marketing system. *European Review of Agricultural Economics*, 21(1): 37-57

Philippidis G., Resano H., Sanjuan A.I. (2014). Shifting Armington trade preferences: A re-examination of the Mercosur –EU negotiatons. *Economic Modelling*, 40:21-32

Romer P. (1994). New goods, old theory, and the welfare costs of trade restrictions. *Journal of Development Economics*, 43, 5-38.

Rosas F., Lence S., Hayes D. (2019). Crop yield responses to prices: a Bayesian approach to blend experimental and market data. *European Review of Agricultural Economics*, 46(4): 551-577

Ryan D.L., Wales T.J. (1999). Flexible and Semiflexible Consumer Demands with Quadratic Engel Curves. *The Review of Economics and Statistics*, 81(2), 277-287.

Sato, K. (1969). Micro and macro constant-elasticity-of-substitution production functions in a multifirm industry. *Journal of Economic Theory*, *1*(4): 438-453.

Sands, R. D., & Leimbach, M., 2003. Modeling agriculture and land use in an integrated assessment framework. *Climatic Change*, *56*(1-2), 185-210.

Witzke H.P., Adenaeur M., Britz W., Heckelei T. (2005). Modelling the EU Sugar Market Scenarios with a Modified Armington Approach. Paper presented at the International Agricultural Trade Research Consortium Symposium, Seville, Spain, June 19-21.

Ye Z., Wu F., Hennessy D.A. (2021). Environmental and economic concerns surrounding restrictions on glyphosate use in corn. *PNAS*, 118(18)

Zhao X., van der Mensbrugghe D., Keeney R., Tyner W. (2020). Improving the way land use change is handled in economic models. Economic Modelling, 84: 13-26