Carbon leakage resulting from afforestation in the UK

Alla Golub, Uris Baldos, Brett Day, and Sabrina Eisenbarth[1]

April 2023

Draft not for quotation and citation

Abstract

Afforestation is an important tool in the climate change mitigation toolbox. We use a computable general equilibrium model and investigate the effects of a 1.5 million hectares afforestation program in the UK. While afforestation helps the UK achieve this individual net zero objective, we show that it leads to land use change and expanded agricultural production abroad. The resulting increase in emissions outside the UK reduces greenhouse gas mitigation benefits from the UK afforestation program. Carbon leakage via land use change abroad amounts to 25% percent of the carbon mitigated via afforestation in the UK.

[1] Alla Golub and Uris Baldos are with Purdue University. Brett Day is with the University of Exeter. Sabrina Eisenbarth is with the University of St. Gallen.

Introduction

Afforestation is an important tool in the climate change mitigation toolbox. The UK Government, for example, pledged to establish 30,000 hectares of new woodland across the UK every year until 2050, to support its commitment to 'net zero' greenhouse gas emissions. As around 70% of the UK's land area is farmland (FAOSTAT 2022), it seems inevitable that some farmland would need to be converted to woodland. Afforestation will likely involve planting on farmland, which in turn will reduce agricultural outputs and exports and increase agricultural and food imports by the UK from other countries, leading to expanded agricultural production in direct UK trading partner countries and beyond. The expansion of agricultural activities abroad is expected to raise GHG emissions, which would reduce the effectiveness of UK greenhouse gas removal through afforestation. The goal of this work is to quantify the carbon leakage due to large-scale afforestation in the UK.

Methods

Carbon leakage is quantified using a version of the Global Trade Analysis Project (GTAP) computable general equilibrium (CGE) model (Corong et al., 2017; Hertel, 1997). The GTAP model is a multi-sector, multi-region comparative static CGE model that estimates production, consumption, trade, and price effects of policies. It takes into account interindustry linkages as well as effects mediated through factor markets and trade. The great strength of the GTAP model is the ease with which it can be modified (Hertel et al. 2010). In this work, we use a variant of the GTAP model nick-named GTAP-AEZ (Hertel et al. 2009). The GTAP-AEZ model incorporates heterogeneous land use and land cover types classified by agroecological zones (AEZs) (Baldos and Corong 2020, Lee et al. 2009). This facilitates analysis of the competition for land within and across regions and the potential for changes in land use driven by climate policies.

Within each model region, we distinguish 18 AEZs, which differ along two dimensions: growing period (6 categories of 60-day growing period intervals), and climatic zones (3 categories: tropical, temperate, and boreal) using data from Global Agro-ecological Zones v.3 (IIASA/FAO 2012). The length of the growing period depends on temperature, precipitation, soil characteristics, and topography. The suitability of each AEZ for the production of alternative crops and livestock is based on currently observed practices, so the competition for land within a given AEZ is constrained to include activities that have been observed to take place in that AEZ. The different AEZs enter as inputs into a national production function for each land-using sector. Within a given use, the returns to land across AEZs will move together if the elasticity of substitution in use is large enough (Hertel et al. 2009).

Even after disaggregating land use by AEZs, there remains substantial heterogeneity within AEZs (Golub et al. 2009). In addition, there are numerous barriers to land conversion between agriculture and forestry, as well as within agriculture. Therefore, we limit the potential for the movement of land from one use to another within an AEZ using a nested constant elasticity of transformation (CET) structure (Villoria et al. 2013, Golub et al. 2013). Within the nested structure, the rent-maximizing landowner first decides on the allocation of land among three land cover types, i.e. forest, cropland, and grazing land, based on relative returns to land. The landowner then decides on the allocation of land among various crops within cropland, again based on relative returns in crop sectors. The CET parameter among the three land cover types is set equal to −0.5 to reflect the flexibility of land conversion over the longer term (Ahmed et al. 2008) and the elasticity of transformation among different crops is set equal to double that for land conversion (−1), reflecting the relatively easier conversion of land among crops within cropland cover (Villoria et al. 2013). Within grazing land, the landowner decides on the allocation of land among ruminant, dairy cattle, and wool sectors based on relative returns to land in these activities. The CET parameter among these three land uses within grazing land is set equal to -10, large by absolute magnitude, to reflect the high mobility of land across these uses. All other parameters in the model are standard GTAP model parameters available in the GTAP data base distribution package (Aguiar et al. 2019).

The analysis is based on version 10.1 of the GTAP database (Aguiar et al. 2019) with the reference year 2014 and the global economy represented with 147 countries and regions and 65 production sectors. To create a regional aggregation of the 147 countries and regions for the model, we analyze UK agricultural, food, and timber export and import flows. The total value of UK exports of these products was 21 billion USD. Of the 147 countries and regions, 21 and 35 countries represent, respectively, 80% and 90% of these exports in value terms. Ireland, France, Germany, Netherlands, and Spain are the largest destinations for UK agricultural, food, and timber exports (Figure 1). The total value of UK imports of these products was 61 bill 2014 USD. 18 and 35 countries are sources of, respectively, 80% and 90% of these imports in value terms. Netherlands, Ireland, Germany, France, and Spain are the largest sources of these imports in the UK (Figure 2). Using the information on the importance of each UK trading partner as measured by the value of exports and imports (Figures 1 and 2), as well as standard GTAP grouping of the 147 countries and regions into 10 geographical regions based on the location of each country/region[2], 147 GTAP countries/regions of the GTAP database are aggregated into 38 countries/regions (Table A1), with the UK and its main trading partners represented as separate countries.

Given our focus on land-using sectors, we keep all land-using sectors in the GTAP data base disaggregated (8 crop sectors, ruminants, raw milk, wool, timber), as well as nonruminants,

[2] These regions are East Asia, Latin America, Middle East and North Africa, North America, Oceania, South East Asia, South Asia, Sub Saharan Africa, Western Europe and Rest of the World.

processed ruminant meat, processed non-ruminant meat, and processed dairy (Table A2). Note, the nonruminants sector (includes swine, poultry, eggs of hens and other birds, other live animals, and edible products of animal origin) does not use land as a direct input into production. Natural resource extraction sectors (fishery, coal, oil, gas, mining) and transport services (air, water, and land) are represented as separate sectors[3]. Other service sectors are aggregated into one sector and manufacturers into another sector.

The model includes emissions from land cover change (Plevin et al. 2014), carbon dioxide (CO_2) emissions from fossil fuel combustion linked to underlying economic activities (Lee 2008), and detailed non-CO_2 GHG emissions by a driver for all sectors of the economy (Chepeliev 2020). Depending on the driver, three types of non-CO_2 GHG emissions are considered in the analysis: associated with sector outputs (e.g., methane emissions from agricultural residue burning), associated with intermediate input usage (e.g., nitrous oxide emissions from fertilizer use in crops), and associated with primary factors (e.g., emissions from livestock capital). Globally, in 2014 agricultural sectors were responsible for 6.2 billion metric tonnes of carbon dioxide equivalent (bill $MtCO_2e$) GHG emissions, excluding emissions from land cover change. 95% of these emissions are methane (CH_4) and nitrous oxide (N_2O). Livestock production makes a significant contribution to agricultural emissions in all regions. In this regional aggregation, China and Sub-Saharan Africa (R_SSA) are the largest contributors of global non-CO_2 emissions from agriculture (Figure B1), and the ruminant meat sector in Sub-Saharan Africa is the single largest agricultural source of non-CO_2 emissions among model regions. China, India, and Indonesia are the largest emitters of non-CO_2 GHGs in crop production (Figure B2), with the paddy rice sector responsible for a very large share of non-CO_2

[3] Extraction of gas (GTAP sector gas) and gas transmission and distribution (GTAP sector gdt) are aggregated together.

GHGs in these regions. Oilseeds sectors are a significant source of non-CO_2 emissions in Brazil and Argentina (Figure B3), while coarse grain sectors are large contributors to the emissions in the USA (Figure B2).

Emissions from land cover change are measured using the emission factors model AEZ-EF (Plevin et al. 2014)[4]. The model is based on carbon stock estimates for above- and below-ground biomass and soil carbon (Gibbs and Yui 2011; Gibbs, Yui et al. 2014), combined with assumptions about carbon dynamics (carbon loss from soils and biomass, mode of conversion, quantity, and species of carbonaceous and other GHG emissions resulting from conversion, carbon remaining in harvested wood products and char, and foregone sequestration) (Plevin et al. 2014). The GTAP model projects a net change in each of the land use classes (forest, cropland, pasture). The emissions from land use change depend on the magnitude of land use transitions (forest to cropland, forest to pasture, cropland to forest, etc.) and emission factors ($MtCO_2e\ ha^{-1}$). The emission factors differ along three dimensions: region, AEZ, and land use transition. Figures C1-3 show a sample of emission factors for tropical, temperate, and boreal AEZs. Emission factors for the conversion of forests to cropland in the tropics are twice larger as in temperate zone and four times larger than in boreal zone, highlighting that the carbon leakage from the domestic afforestation programs depends critically not only on the magnitude of land use changes abroad but also on the location of the conversions.

Experimental design

The UK Government Department for Environment, Food and Rural Affairs (Defra) partners are planning an ambitious tree planting programme, reaching 30,000 ha of trees per year by 2025 (UK Government, 2021). The UK Committee on Climate Change recommends planting a total of 0.9 mill hectares from 2020 to 2050 under the Further Ambition scenario. The Committee also

[4] Mapping from model regions to AEZ-EF regions is available in Table C1.

mentions planting a total of 1.5 million hectares under the Speculative scenario.[5] We are interested in understanding whether extensive woodland planting might affect the prices of agricultural outputs in the UK, and what changes in land use and GHG emissions abroad it may bring. To get a sense of an upper bound of potential effects, we assume that 1.5 million hectares of agricultural land in the UK will be taken out of agricultural production and converted to forests. The trees may be planted for timber and thus harvested in the future, or they may act as permanent carbon storage (conservation forest). In both cases, it is expected that expansive woodland planting will have very little impact on domestic timber output at least until 2050 because of the long rotation forestry system in the UK.

In relative terms, 1.5 million hectares represent 8.7% of the UK agricultural land (cropland and pasture). The GTAP modeling framework is used to simulate an 8.7% reduction in agricultural land in each of the five AEZs present in the UK (temperate AEZs 10-12 and boreal AEZs 15 and 16). Because the afforestation is unlikely to impact UK timber output between now and 2050, we assume that 8.7% of agricultural land is simply taken out of production.

Results

We find that a 1.5 mill ha reduction in agricultural land in the UK is met by a 0.5 mill ha reduction in cropland and a 1 mill ha reduction in pastureland. In boreal AEZs, almost all reductions in agricultural land are met by pastureland, while in temperate AEZs the split is more even with a larger share coming from pasture. Using AEZ-specific areas converted from cropland and pasture to forests in the UK and the emission factors (Plevin et al. 2014), we find that the afforestation program could mitigate 395 mill MtCO_2e.

[5] https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/

The reduction in agricultural land leads to a reduction in agricultural output and exports and an increase in imports of agricultural and food products by the UK (Table 1). Reductions in crop sector outputs are in the 1.3-7.6% range, except for plant-based fiber crops that experience more than 13% reduction. Outputs in ruminant, nonruminant, and raw milk livestock sectors are reduced by 1-2.8%. Note, the nonruminant sector does not use land. The output in this UK sector falls, however, due to increased costs of crop-based feed. In the case of wool, the output is reduced by 26.3%. All agricultural and food sectors in the UK reduce their exports, with the largest reduction in wheat exports (-32.4%). The raw milk sector also shows a large reduction in exports. It should be noted, however, that cross-border trade in raw milk, as well as ruminant and nonruminant animals, is very limited.

The reduction in agricultural land in the UK and subsequent reduction in domestic output results in up to about 6% increases in domestic and relatively small increases in world prices of agricultural commodities (Table 2). The divergence in domestic and global price responses is due to the Armington approach to import demand that differentiates products by origin. The approach permits us to explain the "cross-hauling of similar products" (Hertel 1997), e.g. the UK both exports and imports wheat, and to track bilateral trade flows. The Armington structure in the model is parametrized using econometric estimates of trade elasticities reported by Hertel et al. (2007).

Outside the UK, cropland expands by 0.3 mill ha which comes from 0.19 mill ha of forest land and 0.11 mill ha of pasture. Figure 3 reports changes in land cover around the world. The largest changes are projected in Canada, Sub-Saharan Africa (R_SSA), Brazil, and France. In many regions, cropland expands at the expense of both forest land and pasture. However, in some regions (e.g. rest of the European Union), both cropland and pasture expand, and forest land contracts. These changes in land cover result in a 101 mill MtCO_2e net increase in GHG emissions outside the UK. Most of these emissions result from the conversion of forests to cropland (Figure 4). Carbon leakage via land use change amounts to 25% percent of the carbon mitigated via afforestation in the UK.

In addition to emissions from land cover change, net CO_2 and non-CO_2 emissions from production processes and final consumption decrease by 0.87 mill $MtCO_2e$ per year in the UK, but increase by 1 mill tCO_2e per year in the rest of the world. Carbon leakage via changes in emissions from production processes is more than 100 %. However, these additional annual emissions, when accumulated over time, are still relatively small compared to land-based mitigation from the afforestation in the UK.

Summary and next steps

While afforestation helps countries achieve their individual net zero objectives, we have shown that it leads to land use change and expanded production abroad, resulting in carbon leakage that reduces GHG mitigation benefits from domestic afforestation programs. In the case of the 1.5 mill ha afforestation program in the UK, the emission leakage from land use change abroad could be as high as 25%.

We plan to extend this work in several directions. First, in this paper afforestation program is modeled as a reduction in agricultural land in the UK using a global CGE model that does not capture all the details of agricultural production in the UK. Moreover, we assumed equal relative reductions in each of the UK AEZs. A better option is to model UK afforestation and corresponding farmers' decisions using the Land, Environment, Economics and Policy Institute (LEEP) farm model of agricultural land use and production. The model is econometrically estimated at the grid cell level[6]. The LEEP farm model predicts the decisions

[6] https://www.leep.exeter.ac.uk/nevo/documentation/

made by profit-maximizing farmers about how to allocate their agricultural land between arable and grassland and, within these uses, what crops and livestock to produce in each grid cell. The share of each grid cell devoted to agricultural activity (wheat, dairy cattle, sheep, etc.) is a function of rain, temperature, slope, lagged prices, and policy variables. The policy variable is the share of each grid cell that cannot be used for agricultural production, e.g. share for afforestation. Given the afforestation policy, the model calculates changes in land use and agricultural output in each grid cell. These changes in agricultural output can be aggregated to the UK level and passed to a computable general equilibrium (CGE) model to measure impacts on UK exports and imports, land use and agricultural production in the rest of the world, and carbon leakage.

Second, climate change will affect agricultural yields in the UK and around the globe. We will develop an approach to consistently model different climate scenarios within the UK farm and the CGE models. For this task, we plan to use the library of climate change crop yield projections produced by the Agricultural Model Intercomparison and Improvement Project based on Coupled Model Intercomparison Project Phase 5 (CMIP5)[7] (Rosenzweig *et al*. 2014, Villoria et al. 2016). Specifically, we plan to use crop yield projections from the Environmental Policy Integrated Climate Model (EPIC Model) (Izaurralde *et al*. 2006) which has the largest coverage of crops (15 crops[8]) for four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). To model the impacts of climate change in the CGE model, the gridded data will be aggregated across time and space using gridded crop production maps from Monfreda *et al*.

[7] Although the latest AGMIP yield projections are available for CMIP6, the crop coverage of these projections are limited to maize, rice, soybean and wheat.

[8] Maize, wheat, soybean, rice, barley, managed grass, millet, rapeseed, sorghum, sugarcane, drybean, cassava, cotton, sunflower, groundnut.

(2008) to calculate crop productivity shocks across scenarios. The carbon leakage will be reevaluated for each climate scenario.

Finally, this preliminary analysis presented here focuses on the afforestation program much larger than the one recommended by the UK Committee on Climate Change. The purpose of the analysis was to get a sense of the upper bound of potential effects. The next steps include the analysis of tree planting programs that are more likely to be implemented.

References

Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1), 1-27.

Baldos, U., & Corong, E. (2020). *Development of GTAP 10 Land Use and Land Cover Data Base for years 2004, 2007, 2011 and 2014* (GTAP Research Memorandum No. 36). Purdue University, West Lafayette, IN: Global Trade Analysis Project (GTAP).

Chepeliev, M. (2020). *Development of the Non-CO2 GHG Emissions Database for the GTAP 10A Data Base* (GTAP Research Memorandum No. 32). Purdue University, West Lafayette, IN: Global Trade Analysis Project (GTAP). Retrieved from https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5993

Corong, E., Hertel, T., McDougall, R., Tsigas, M., & van der Mensbrugghe, D. (2017). The Standard GTAP Model, Version 7. *Journal of Global Economic Analysis*, 2(1), 1-119.

Food and Agriculture Organization of the United Nations (2022). FAOSTAT statistical database. https://www.fao.org/faostat/en/#home

Golub, A., Henderson, B., Hertel, T., Gerber, P., Rose, S., & Sohngen, B. (2013). Global climate policy impacts on livestock, land use, livelihoods and food security. *Proceedings of the National Academy of Sciences, 110*(52), pp. 20894-20899.

Golub, A., Hertel, T., & Sohngen, B. (2009). Land Use Modelling in Recursively Dynamic GTAP Framework, in *Economic Analysis of Land Use in Global Climate Change Policy*, edited by Thomas Hertel, Steven Rose, and Richard Tol. Routledge.

Hertel, T. W., ed. (1997). Global Trade Analysis: Modeling and Applications. United Nations, New York: Cambridge University Press.

Hertel, T. W., Golub, A. A., Jones, A., O'Hare, M., Plevin, R., & Kammen, D. (2010). Global land use and greenhouse gas emissions impacts of U.S. maize ethanol: estimating market-mediated responses. *BioScience*, *60*(3), pp. 223-231.

Hertel, T., Hummels, D., Ivanic, M., & Keeney, R. (2007). How confident can we be of CGE-based assessments of Free Trade Agreements? *Economic Modelling*, Volume 24, Issue 4, pp. 611-635.

Hertel, T., Lee, H.-L., Rose, S., & Sohngen, B. (2009). Modeling Land-use Related Greenhouse Gas Sources and Sinks and Their Mitigation Potential. In T.W. Hertel, S. Rose, and R. Tol, eds. *Economic Analysis of Land Use in Global Climate Change Policy*. London and New York: Routledge, pp. 123–154.

IIASA/FAO (2012). Global Agro-ecological Zones (GAEZ v3.0) (p. 196). IIASA, Laxenburg, Austria; FAO, Rome, Italy. http://www.gaez.iiasa.ac.at/docs/ GAEZ_Model_Documentation.pdf

Izaurralde, R., Williams, J., McGill, W., Rosenberg, N., & Jakas, M. (2006). Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecol. Model.* 192, 362–384.

Lee, H.-L. (2008). The combustion-based CO2 emissions data for GTAP Version 7 data base. Global Trade Analysis Project (GTAP Resource, 1143). Available online at https://www.gtap.agecon.purdue.edu/resources/download/4470.pdf.

Lee, H.-L., Hertel, T., Rose, S., & Avetisyan, M. (2009). An Integrated Land Use Data Base for CGE Analysis of Climate Policy Options. In T.W. Hertel, S. Rose, and R. Tol, eds. *Economic Analysis of Land Use in Global Climate Change Policy*. London and New York: Routledge, pp. 73–91.

Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cycles* 22.

Plevin, R., Gibbs, H., Duffy, J., Yui, S., & Yeh, S. (2014). *Agro-ecological Zone Emission Factor (AEZ-EF) Model (v47)* (GTAP Technical Paper No. 34). Purdue University, West Lafayette, IN: Global Trade Analysis Project (GTAP).

Rosenzweig, C. *et al.* (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci.* 111, 3268–3273.

UK Government (2021). *The England Trees Action Plan 2021-2024*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/987432/england-trees-action-plan.pdf

Villoria, N. B. *et al.* (2016). Rapid aggregation of global gridded crop model outputs to facilitate cross-disciplinary analysis of climate change impacts in agriculture. *Environ. Model. Softw.* 75, 193–201.

Table 1 Changes in UK output, export, and import quantity indices of agricultural and food commodities due to 1.5 mill ha reduction of agricultural land in the UK, %.

Sector	Output	Export	Import
wheat	-4.6	-32.4	16.6
crsgrns	-4.4	-11.8	3.7
fruitveg	-7.6	-16.7	3.2
oilsds	-6.0	-18.2	3.9
sugarcrps	-1.3	-15.8	1.1
pbfiber	-13.3	-20.6	1.1
othercrps	-2.9	-9.5	0.7
ruminant	-2.1	-9.9	5.6
nonruminant	-1.0	-2.3	0.2
raw_milk	-2.8	-28.6	5.2
wool	-26.3	-26.8	-0.8
pr_rum	-1.2	-3.9	1.4
pr_nonrum	-1.2	-3.2	0.9
dairy	-2.5	-6.5	2.3
procfood	-0.3	-0.5	0.0

Table 2 Changes in UK and global price indices of agricultural and food commodities due to 1.5 mill ha reduction of agricultural land in the UK, %.

Sector	UK price index	Global price index
wheat	5.25	0.16
crsgrns	5.37	0.07
fruitveg	5.76	0.07
oilsds	4.43	0.06
sugarcrps	4.15	0.05
pbfiber	5.09	0.03
othercrps	1.80	0.08
ruminant	3.72	0.10
nonruminant	1.02	0.02
raw_milk	4.83	0.14
wool	2.74	0.06
pr_rum	0.67	0.03
pr_nonrum	0.45	0.02
dairy	1.21	0.04
procfood	0.16	0.01

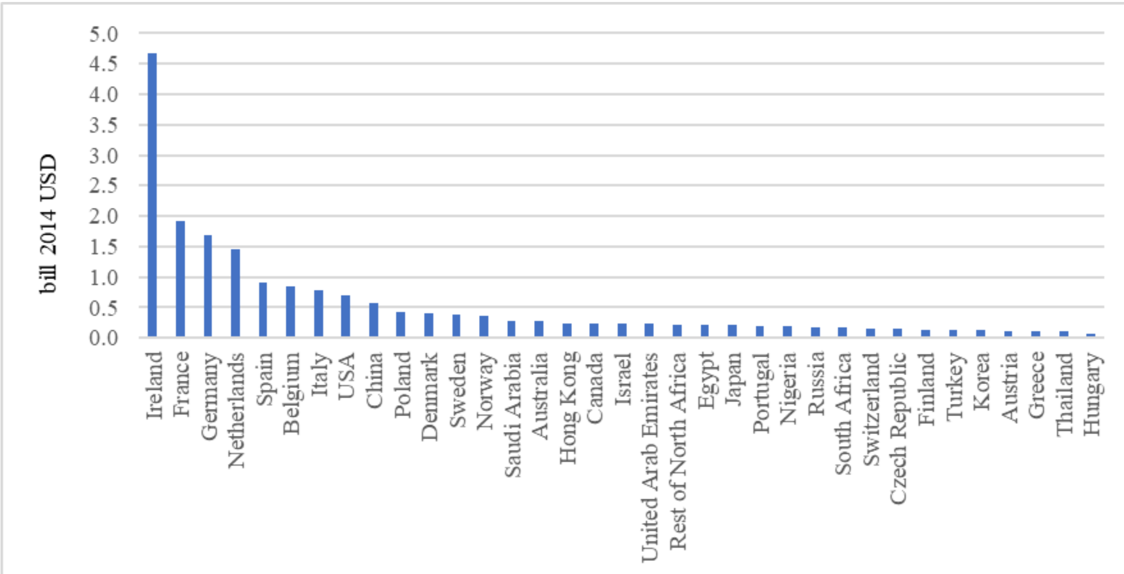

Figure 1 UK exports of agriculture, food, and timber by destination, bill 2014 USD. 35 trading partners, representing 90% of UK exports in these products by value, are sorted by the export flow. The first 21 countries (from Ireland to Egypt) represent 80% of UK exports.

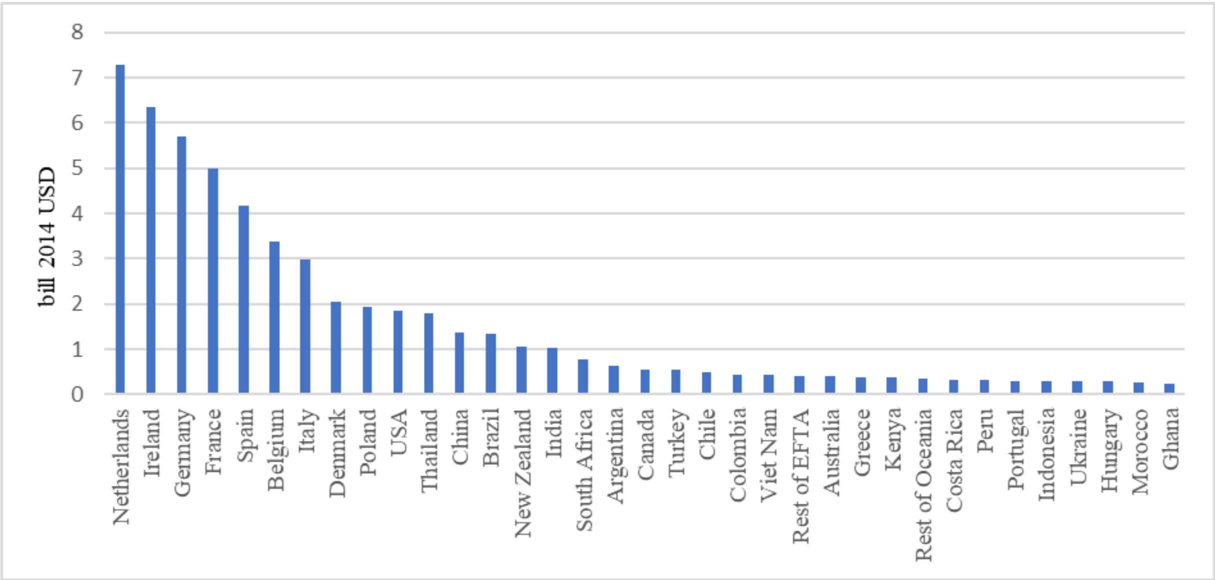

Figure 2 UK imports of agriculture, food, and timber by source, bill 2014 USD. 35 trading partners, representing 90% of UK imports of these products by value, are sorted by import flow. The first 18 countries (from the Netherlands to Canada) provide 80% of the UK's agriculture, food, and timber imports.

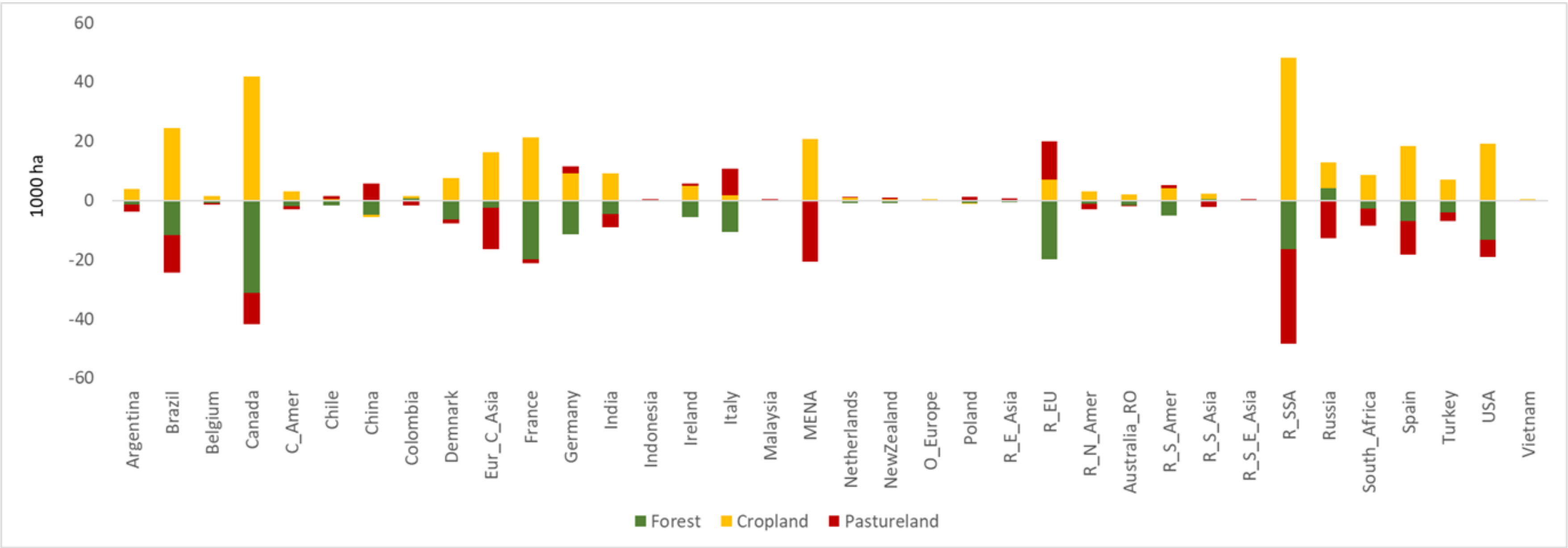

Figure 3 Changes in land cover around the world due to a 1.5 mill ha reduction of agricultural land in the UK, 1000 ha

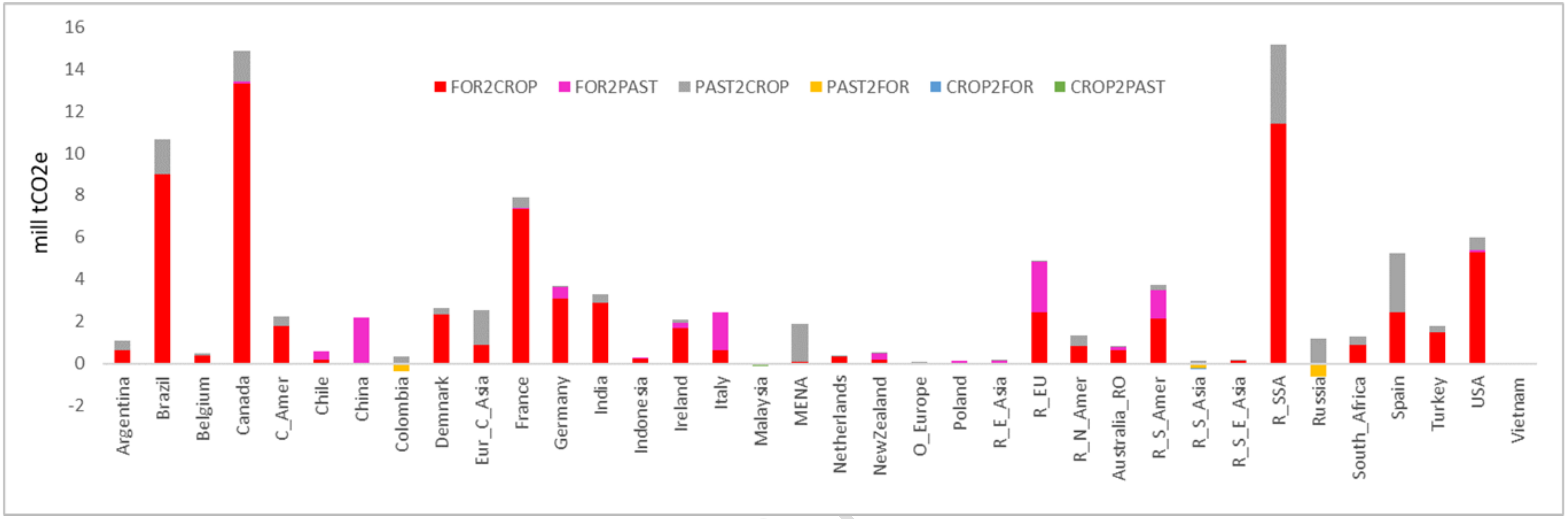

Figure 4 Changes in emissions per conversion type, mill tCO_2e

Appendix A

Table A1. The mapping from disaggregated 147 GTAP regions to aggregated 38 regions

Aggregated regions			Disaggregated regions
No.	Code	Description	
1	Argentina	Argentina	arg
2	Brazil	Brazil	bra
3	Belgium	Belgium	bel
4	Canada	Canada	can
5	C_Amer	Central America	cri, gtm, hnd, nic, pan, slv, xca, dom, jam, pri, tto, xcb
6	Chile	Chile	chl
7	China	China	chn
8	Colombia	Colombia	col
9	Denmark	Denmark	dnk
10	Eur_C_Asia	Europe and Central Asia	srb, alb, blr, ukr, xee, xer, kaz, kgz, tjk, xsu, arm, aze, geo
11	France	France	fra
12	Germany	Germany	deu
13	India	India	ind
14	Indonesia	Indonesia	idn
15	Ireland	Ireland	irl
16	Italy	Italy	ita
17	Malaysia	Malaysia	mys
18	MENA	Middle East and North Africa	bhr, irn, irq, isr, jor, kwt, lbn, omn, pse, qat, sau, syr, are, xws, egy, mar, tun, xnf
19	Netherlands	Netherlands	nld
20	NewZealand	New Zealand	nzl
21	O_Europe	Other Europe	che, nor, xef
22	Poland	Poland	pol
23	R_E_Asia	Rest of East Asia	hkg, jpn, kor, mng, twn, xea
24	R_EU	Rest of European Union	aut, bgr, hrv, cyp, cze, est, fin, grc, hun, lva, ltu, lux, mlt, prt, rou, svk, svn, swe
25	R_N_Amer	Rest of North America	mex, xna
26	Australia_RO	Australia and Rest of Oceania	aus, xoc
27	R_S_Amer	Rest of South America	bol, ecu, pry, per, ury, ven, xsm
28	R_S_Asia	Rest of South Asia	brn, khm, lao, bgd, npl, pak, lka, xsa
29	R_S_E_Asia	Rest of Southeast Asia	phl, sgp, tha, xse
30	R_SSA	Rest of Sub-Saharan Africa	ben, bfa,cmr, civ, gha, gin, nga, sen, tgo, xwf, scf, xac, eth, ken, mdg, mwi, mus, moz, rwa, sdn, tza, uga, zmb, zwe, xec, bwa, nam, xsc
31	RoW	Rest of World	xtw
32	Russia	Russia	rus
33	South_Africa	South Africa	zaf
34	Spain	Spain	esp
35	Turkey	Turkey	tur
36	UK	United Kingdom	gbr
37	USA	United States of America	usa
38	Vietnam	Vietnam	vnm

Table A2. The mapping from disaggregated 65 GTAP sectors to aggregated 30 sectors

	Aggregated sectors		Disaggregated sectors
No.	Code	Description	
1	paddyrice*	paddy rice	pdr
2	wheat*	wheat	wht
3	crsgrns*	cereal grains nec	gro
4	fruitveg*	vegetables, fruit and nut	v_f
5	oilsds*	oil seeds	osd
6	sugarcrps*	sugar crop, sugar beet	c_b
7	pbfiber*	plant-based fiber	pfb
8	othercrps*	crops nec	ocr
9	ruminant*	bovine cattle, sheep and goats, horses	ctl
10	nonruminant	animal products nec	oap
11	raw_milk*	raw milk	rmk
12	wool*	wool, silk-worm cocoons	wol
13	forest*	forestry	frs
14	fishery	fishing	fsh
15	pr_rum	bovine meat products	cmt
16	pr_nonrum	processed nonruminants	omt
17	dairy	dairy products	mil
18	procfood	processed food	vol, pcr, sgr, ofd, b_t
19	coal	coal	coa
20	oil	oil	oil
21	gas	gas	gas, gdt
22	oxt	other extraction	oxt
23	oil_pcts	petroleum and coal products	p_c
24	electricity	electricity	ely
25	water_transp	water transport	wtp
26	air_transp	air transport	atp
27	other_transp	transport nec	otp
28	chm	chemical products	chm
29	mnfcing	manufacturing	tex, wap, lea, lum, ppp, bph, rpp, nmm, i_s, nfm, fmp, ele, eeq, ome, mvh, otn, omf
30	services	services	wtr, cns, trd, afs, whs, cmn, ofi, ins, rsa, osg, ros, osg, edu, hht, dwe

*Sectors that use land input in the model.

Appendix B

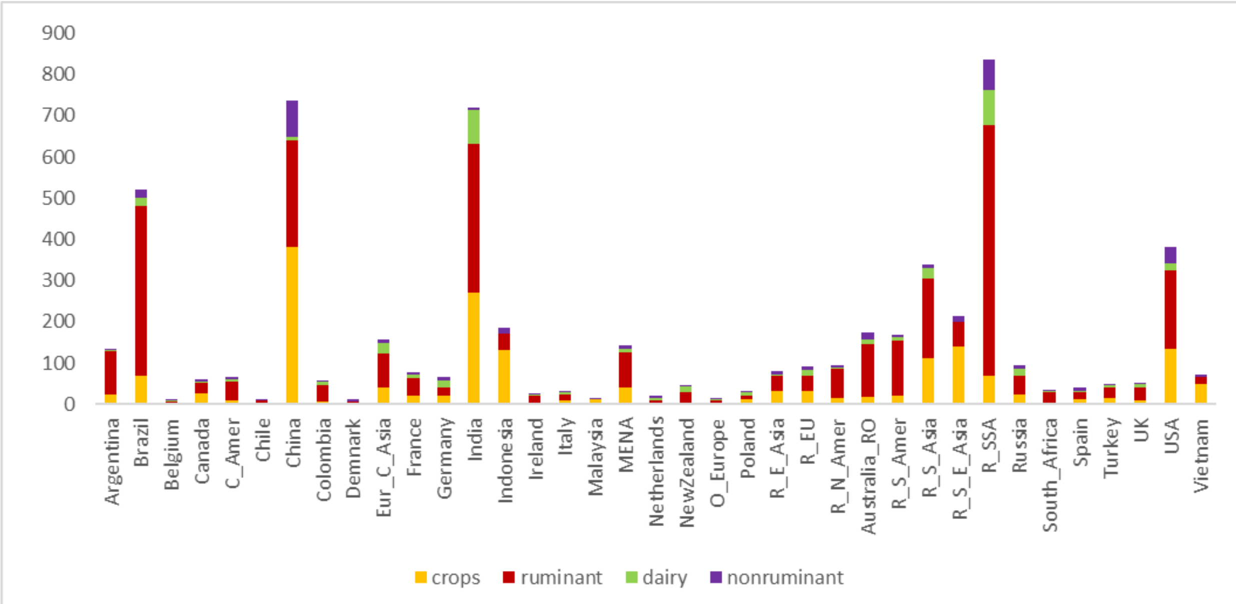

Figure B1 Non-CO_2 GHG emissions by agricultural sector group and region, mill $MtCO_2e$. The ruminant category includes emissions from model sectors ruminant and wool.

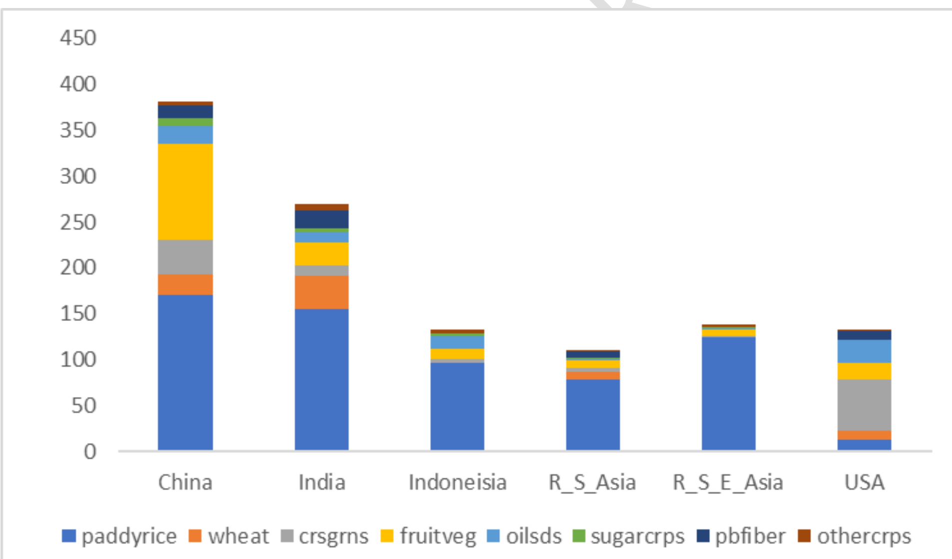

Figure B2 Non-CO_2 GHG emissions by crop sector and each of the six largest emitters in the model, mill $MtCO_2e$.

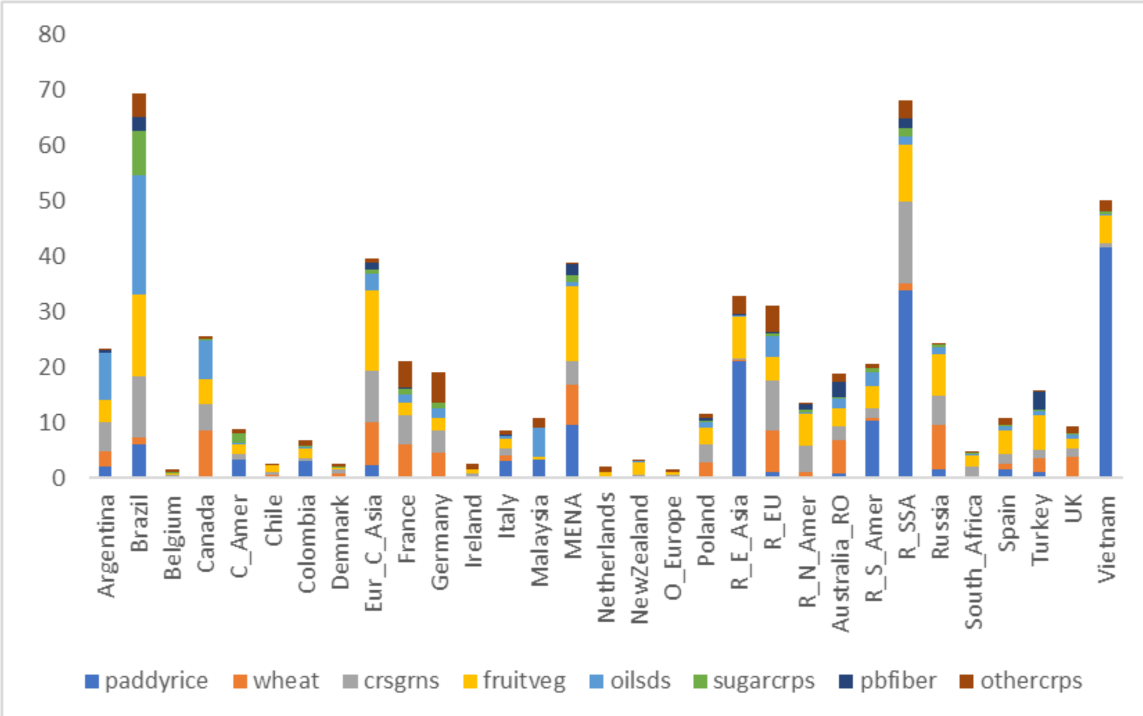

Figure B3 Non-CO_2 GHG emissions by crop sector and region (excluding the six largest emitters shown in Figure 2B), mill $MtCO_2e$.

Appendix C

Table C1 The mapping from the CGE model regions to AEZ-EF model regions

Model regions			AEZ-EF regions	
No.	Code	Description	Code	Description
1	Argentina	Argentina	S_o_Amer	South and Other Americas
2	Brazil	Brazil	BRAZIL	Brazil
3	Belgium	Belgium	EU27	European Union 27
4	Canada	Canada	CAN	Canada
5	C_Amer	Central America	C_C_Amer	Central and Carrebian Americas
6	Chile	Chile	S_o_Amer	South and Other Americas
7	China	China	CHIHKG	China and HongKong
8	Colombia	Colombia	S_o_Amer	South and Other Americas
9	Denmark	Denmark	EU27	European Union 27
10	Eur_C_Asia	Europe and Central Asia	Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union Other
11	France	France	EU27	European Union 27
12	Germany	Germany	EU27	European Union 27
13	India	India	INDIA	India
14	Indonesia	Indonesia	Mala_Indo	Malaysia and Indonesia
15	Ireland	Ireland	EU27	European Union 27
16	Italy	Italy	EU27	European Union 27
17	Malaysia	Malaysia	Mala_Indo	Malaysia and Indonesia
18	MENA	Middle East and North Africa	MEAS_NAfr	Middle East and North Africa
19	Netherlands	Netherlands	EU27	European Union 27
20	NewZealand	New Zealand	Oceania	Oceania
21	O_Europe	Other Europe	Oth_Europe	Rest of European Countries
22	Poland	Poland	EU27	European Union 27
23	R_E_Asia	Rest of East Asia	E_Asia	East Asia
24	R_EU	Rest of European Union	EU27	European Union 27
25	R_N_Amer	Rest of North America	C_C_Amer	Central America and Carrebian
26	Australia_RO	Australia and Rest of Oceania	Oceania	Oceania
27	R_S_Amer	Rest of South America	S_o_Amer	South and Other Americas
28	R_S_Asia	Rest of South Asia	R_S_Asia	Rest of South Asia
29	R_S_E_Asia	Rest of Southeast Asia	R_SE_Asia	Rest of South East Asia
30	R_SSA	Rest of Sub-Saharan Africa	S_S_AFR	Sub Sharan Africa
31	RoW	Rest of World	N/A	N/A
32	Russia	Russia	Russia	Russia
33	South_Africa	South Africa	S_S_AFR	Sub Saharan Africa
34	Spain	Spain	EU27	European Union 27
35	Turkey	Turkey	Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union Other
36	UK	United Kingdom	EU27	European Union 27
37	USA	United States of America	USA	United States of America
38	Vietnam	Vietnam	R_SE_Asia	Rest of South East Asia

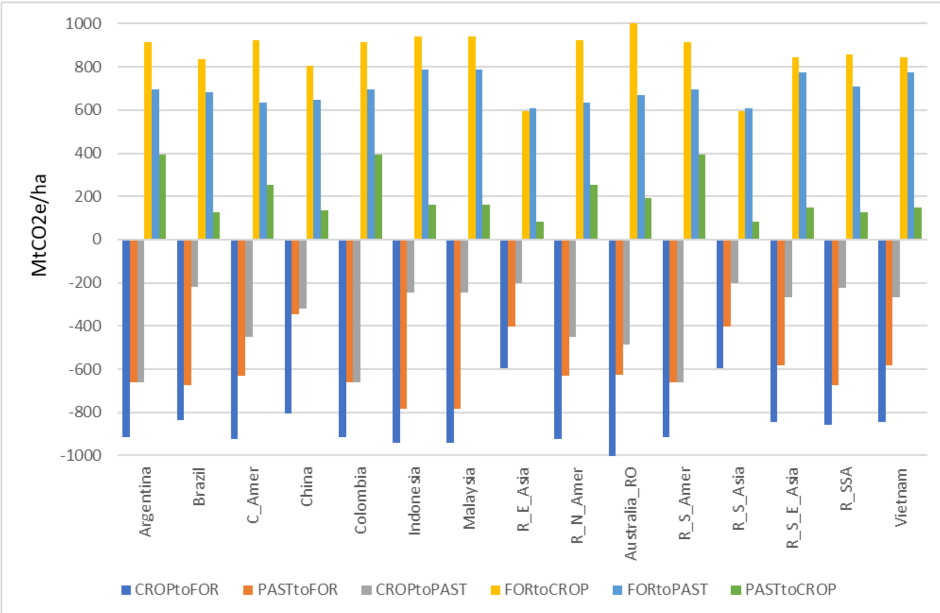

Figure C1. Region and land use transition specific emission factors in tropical AEZ6, $MtCO_2e$ ha^{-1}. Positive (negative) values indicate a loss (gain) of carbon to (from) the atmosphere and a reduction (increase) in carbon storage.

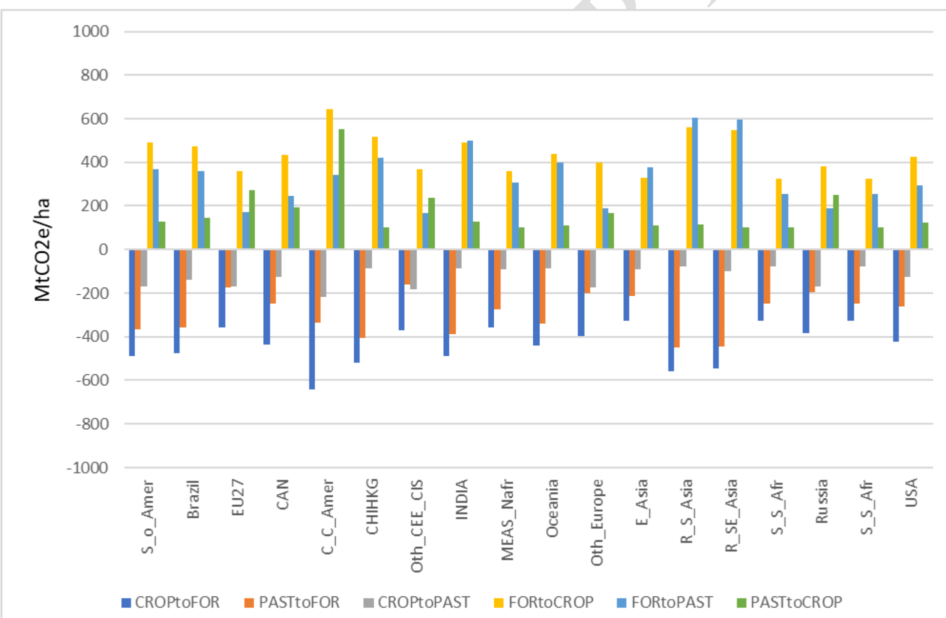

Figure C2. Region and land use transition specific emission factors in temperate AEZ10, $MtCO_2e$ ha^{-1}. Positive (negative) values indicate a loss (gain) of carbon to (from) the atmosphere and a reduction (increase) in carbon storage.

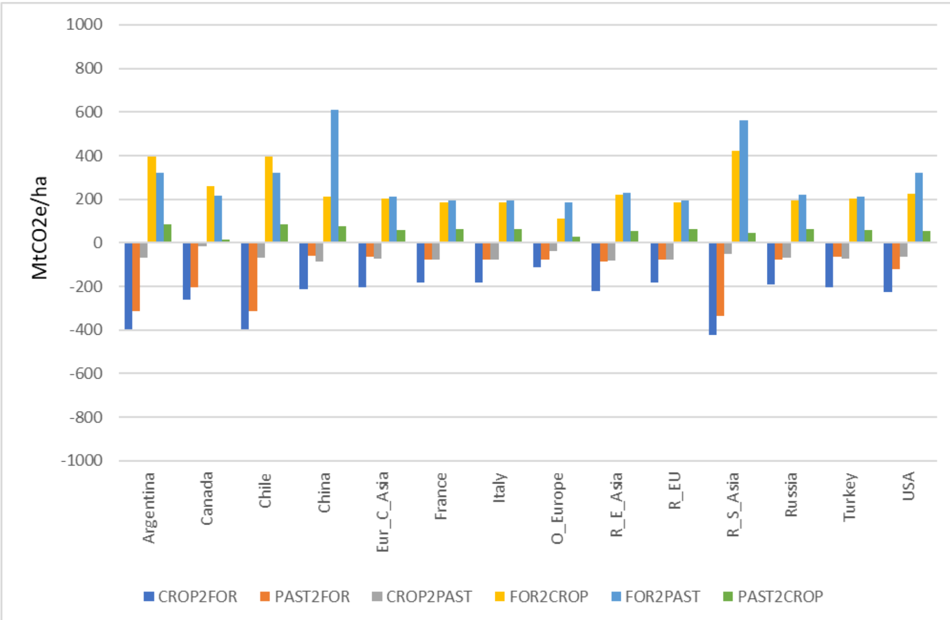

Figure C3. Region and land use transition specific emission factors in boreal AEZ13, $MtCO_2e$ ha^{-1}. Positive (negative) values indicate a loss (gain) of carbon to (from) the atmosphere and a reduction (increase) in carbon storage.