Organisation for Economic Co-operation and Development

COM/TAD/CA/ENV/EPOC(2019)7/FINAL

Unclassified **English - Or. English**

31 July 2019

TRADE AND AGRICULTURE DIRECTORATE
ENVIRONMENT DIRECTORATE

Joint Working Party on Agriculture and the Environment

Agri-environmental Indicators: Ammonia and Greenhouse Gas Emissions

.

This document presents a summary of ammonia and greenhouse gas emissions indicators trends in OECD countries. It also discusses potential drivers and the relationship between productivity and greenhouse gas emissions intensities.

This work is mandated under the 2017-18 PWB intermediate output 3.2.3.1.1. It was written by Santiago Guerrero and Maho Nakagawa (University of Strasbourg).

Santiago GUERRERO, TAD/ARP (santiago.guerrero@oecd.org) +33 (0)1 45 24 15 28

JT03450106

Key Messages

This report summarises the most recent trends in ammonia and greenhouse gas emissions (GHG) indicators, the main air pollutants from agricultural activities, from the OECD agri-environmental indicators database (OECD, 2018[1]). It also conducts an econometric exercise to estimate the relationship between GHG intensities and labour productivity and discusses how New Zealand is tackling GHG emissions intensities. The main messages of the report are:

- Trends in agricultural ammonia and greenhouse gas emissions indicate a deterioration of agriculture's performance in the OECD area. While GHG emissions were practically unchanged in the period 1993-2005, these emissions increased by 0.2% yearly in OECD countries from 2003 to 2015. Ammonia emissions in the OECD region decreased in the period 2003-15 but at a slower speed than they did in the period 1993-2005.
- OECD countries should especially address the observed increasing emissions from agricultural soils, mainly from the use of synthetic fertilisers, as they explain most of the rise of agricultural GHG emissions during the period 2003-15.
- Countries' capacities to produce agricultural goods while minimizing GHG emissions have weakened. GHG emissions per dollar of agricultural production (emissions intensities) kept declining in OECD countries in the period 2003-15, but at lower speed than they did in the period 1993-2005.
- In highly productive OECD countries, further labour productivity improvements may not translate into a reduction of GHG emissions intensities. OECD countries may be reaching a productivity level at which further improvements may even induce more GHG emissions per unit of output.
- The New Zealand case illustrates that reducing emissions intensities, while maintaining agricultural production is a reachable outcome when there are policies in place focused on research and development, particularly targeting farm profitability, productivity and emissions intensity reductions and low levels of distortionary support to agriculture.

1. The role of agriculture on greenhouse gas and ammonia emissions

Agricultural activities affect air quality mainly via greenhouse gas (GHG) and ammonia (NH_3) emissions. Agriculture is the main emitter of methane (CH_4) and nitrous oxide (N_2O), two non-CO_2 greenhouse gases with more potential to warm the atmosphere than carbon dioxide (CO_2), but with a shorter lifespan (IPCC, 2014[2]). GHG emissions from agriculture represent 10-12% of total global GHG emissions (Smith et al., 2014[3]). Worldwide, nearly 40% of agricultural GHG emissions come from ruminants' digestive process (enteric fermentation) and 30% from agricultural soils; the remaining 30% is from rice cultivation, biomass burning and manure management (Tubiello et al., 2013[4]).

Agriculture's link to greenhouse gas (GHG) emissions and climate change is complex. While the sector is a contributor of GHGs to the atmosphere, agricultural soils can act as carbon sinks depending on how they are managed (OECD, 2008[4]). Agriculture is not only responsible for GHG emissions due to the direct management and operation of farms but also more indirectly due to the conversion of natural habitats such as forested lands and peatlands to agricultural fields. The agricultural sector is projected to be the second sector to contribute the most to economic damages from climate change, only after losses associated with health (OECD, 2015[5]). The impacts on the sector are likely to be differentiated by space, time and crop, with some regions, especially in higher latitudes, being benefited and those near the Tropics suffering the most (Smith et al., 2014[3]; OECD, 2015[5]). In some regions, higher CO_2 concentrations in the atmosphere, which tend to improve photosynthesis and increase yields, could more than compensate the potentially negative effects of hotter temperatures (Barros et al., 2015[6]; Murgida et al., 2014[7]).

Agriculture also accounts for 80-90% of total ammonia emissions globally (Bouwman et al., 1997[8]; Zhang et al., 2010[9]; Xu et al., 2019[10]), via volatilization from livestock manure and synthetic mineral N fertiliser application (Bouwman et al., 1997[8]). Ammonia emissions are associated with two major types of environmental problems: acidification and eutrophication (OECD, 2008[11]). When combined with water in the atmosphere or after deposition, ammonia contributes to acidification of soil and water. Excess soil acidity may harm certain types of terrestrial and aquatic ecosystems. Deposition of ammonia can also increase nitrogen levels in soil and water, which may lead to eutrophication –algal and plant growth due to excess nutrients- in receiving aquatic ecosystems (OECD, 2008[11]). Humans' exposure to high concentrations of NH_3 can affect the respiratory track and lung function (OECD, 2018[12]). NH_3 is also a precursor of particulate matter (PM) a potent air pollutant that poses risks to human health (OECD, 2018[12]).

Both GHG and ammonia emissions are transboundary pollutants, that is, they affect areas beyond those where they are emitted. Therefore, international accords are paramount to effectively reduce such emissions.

2. Trends in GHG and ammonia emissions

This report mainly focuses on three agri-environmental indicators: agricultural greenhouse gas emissions, intensity of agricultural greenhouse gas emissions and ammonia emissions. Box 2.1 clarifies the indicators used and the data available before the rest of this section analyses recent trends.

Box 2.1. Indicators and data used

Agricultural greenhouse gas emissions (thousand tonnes)

The data to create this indicator was obtained from the United Nations Framework Convention on Climate Change (UNFCCC) database on national inventory reports (NIR) (UNFCCC, 2018[13]) for OECD countries included in Annex I of the UNFCCC. For OECD countries not included in Annex I, data were compiled directly by the OECD via questionnaire. While the UNFCCC requires countries to use common reporting format (CRF) tables to ensure robust and standardised reporting, estimates made by individual member countries may vary depending on factors and methods used in their own calculations. In addition, assumptions made in agricultural GHG emission calculations simplify complex agricultural systems introducing uncertainty into the estimate of GHG emissions. Although the OECD questionnaire for OECD countries not included in Annex I follows the CRF tables to facilitate the treatment of the responses, the same caveats as for UNFCCC inventories applies. The categories covered according to the IPCC nomenclature are: 3A-Enteric fermentation, 3B-Manure management, 3C-Rice cultivation, 3D-Agricultural soil, 3E-Prescribed burning of savannas, 3F- Field burning of agricultural residues, 3G-Liming, 3H-Urea application, 3I-Other carbon-containing fertilisers, 3J – Others.

Intensity of agricultural greenhouse gas emissions (kg of CO_2 equivalent/USD)

This indicator measures agricultural emissions of greenhouse gases per agricultural gross production value. It helps to assess whether agricultural production value is decoupled with greenhouse gas emissions of the sector. Agricultural gross production value measures production in monetary terms at the farm gate level and it is calculated by multiplying gross production quantities by output prices at farm gate (FAOSTAT, 2018[14]). Since intermediate uses within the agricultural sector (seed and feed) have not been subtracted from production data, this value of production aggregate refers to the notion of "gross production" (FAOSTAT, 2018[14]). It is important to recognise that distortionary policies such as market price support may affect the gross production value because it is measured at the farm gate level. A more appropriate measure of value would use non-distorted international prices, however, no such dataset is available at the global level.

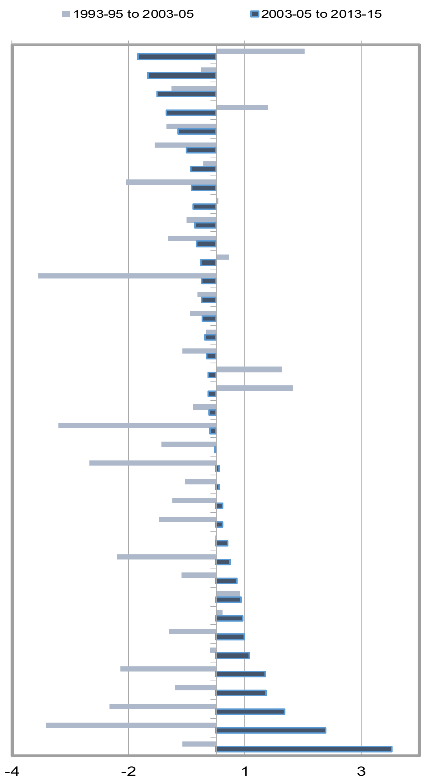
Ammonia emissions (thousand tonnes)

Ammonia emissions for OECD countries were obtained from data officially submitted by the Parties to the Convention on Long Range Transboundary Air Pollution (CLRTAP) to the European Monitoring and Evaluation Programme (EMEP) programme via the United Nations Economic Commission for Europe (UNECE). Emissions reported under the CLRTAP tend to follow a bottom-up approach: they are calculated by applying emissions factors to geo-localised farm activities (Morán et al., 2016[15]). While reporting under the CLRTAP ensures standardised formats and facilitates consistency, there could be differences in terms of emissions factors and methodologies used across countries. Moreover, emissions are known to vary through the year and a national figure can mask within countries spatial heterogeneity (OECD, 2018[12]).

2.1. Agricultural GHG emissions in the OECD area are rising

Agricultural greenhouse gas emissions in the OECD area increased by 26 million tonnes of CO_2 equivalent, from 1.32 Gt of CO_2 equivalent in the period 2003-05 to 1.35 Gt of CO_2 equivalent in 2013-15 (Figure 2.1). The average annual growth rate for this period was 0.2%, while the annual growth rate in the period 1993-2005 was slightly negative (-0.02%). Compared to the period 1993-2005, in the most recent period of analysis fewer countries registered negative growth rates and only five countries, Greece, Israel, Italy, Spain and the United Kingdom attained growth rates lower than -0.5%, while in the period 1993-2005, twenty-one countries did.

Figure 2.1. Agricultural GHG emissions in OECD countries are increasing



	Average			Change in agricultural GHG emissions				Share of agriculture in national total GHG emissions	Share in total OECD agriculture GHG emissions
	Thousand tonnes, CO_2 equivalent			Thousand tonnes, CO_2 equivalent	Average annual % change	Thousand tonnes, CO_2 equivalent	Average annual % change	%	%
	1993-95	2003-05	2013-15	1993-95 to 2003-05		2003-05 to 2013-15		2013-15	2013-15
Spain	32 932	38 339	33 523	5 407	2	-4 816	-1	10.2	2.5
Greece	9 322	9 080	8 080	-241	-0.3	-1 000	-1.2	8	0.6
Italy	35 196	32 595	29 475	-2 601	-1	-3 120	-1	6.8	2.2
Israel[1]	2 072	2 264	2 079	192	0.9	-184	-0.8	3	0.2
United Kingdom	48 653	44 690	41 905	-3 963	-1	-2 784	-1	7.8	3.1
Denmark	12 224	11 006	10 457	-1 218	-1.0	-549	-0.5	20	0.8
Slovenia	1 827	1 787.4	1 712	-39	0	-75	0	9.9	0.1
Belgium	12 261	10 498	10 068	-1 763	-1.5	-430	-0.4	9	0.7
Australia	74 226.7	74 597	71 770.0	370	0.0	-2 827	0	13	5.3
EU15	**373 000**	**354 592**	**341 936**	**-18 408**	**-0.5**	**-12 656**	**-0.4**	**10**	**25.3**
Sweden	7 755.2	7 138	6 909.4	-617	-0.8	-229	0	13	0.5
Chile[2]	13 239	13 538	13 254	300	0.2	-284	-0.3	12	1.0
Slovak Republic	3 643.4	2 672	2 607.5	-972	-3.1	-64	0	6	0.2
Norway	4 696	4 549	4 441	-146	-0.3	-108	-0.2	8	0.3
Ireland	19 882	19 024	18 585	-858	0	-439	0	32.0	1.4
France	80 398	78 985	77 560	-1 413	-0.2	-1 425	-0.2	16	5.7
Japan	36 812	34 757	34 190	-2 055	-1	-567	0	2.5	2.5
New Zealand	35 579	39 850	39 312	4 271	1.1	-538	-0.1	49	2.9
Canada	52 190	59 486	58 684	7 296	1	-802	0	8.2	4.3
Portugal	7 024	6 756	6 677	-268	-0.4	-78	-0.1	10	0.5
Netherlands	24 387	18 531	18 338	-5 856	-3	-193	0	9.6	1.4
Austria	7 865	7 154	7 143	-711	-0.9	-11	0.0	9	0.5
Czech Republic	9 862	7 920	7 961	-1 942	-2	41	0	6.2	0.6
Finland	6 815	6 460	6 499	-355	-0.5	39	0.1	11	0.5
Switzerland	6 397	5 936	6 005	-461	-1	69	0	12.1	0.4
Korea	22 826	20 695	20 944	-2 131	-1.0	250	0.1	3	1.5
OECD	**1 330 088**	**1 327 300**	**1 354 162**	**-2 788**	**0**	**26 862**	**0**	**8.6**	**100**
Poland	34 909	29 410	30 147	-5 499	-1.7	737	0.2	8	2.2
Germany	67 541	63 648	65 994	-3 893	-1	2 346	0	7.2	4.9
United States	505 400	526 687	549 940	21 287	0.4	23 253	0.4	8	40.6
Hungary	6 121	6 193	6 483	72	0	290	0	11.0	0.5
Luxembourg	745	687	721	-58	-0.8	35	0.5	7	0.1
Mexico	95 307	94 412	99 971	-895	0	5 559	1	14.8	7.4
Lithuania	4 897	4 153	4 518	-745	-1.6	365	0.8	23	0.3
Iceland	589	548	597	-41	-1	49	1	12.8	0.0
Latvia	2 791	2 320	2 609	-472	-1.8	290	1.2	23	0.2
Estonia	1 481	1 101	1 326	-380	-3	226	2	6.5	0.1
Turkey	42 226	39 836	53 673	-2 390	-0.6	13 837	3.0	12	4.0

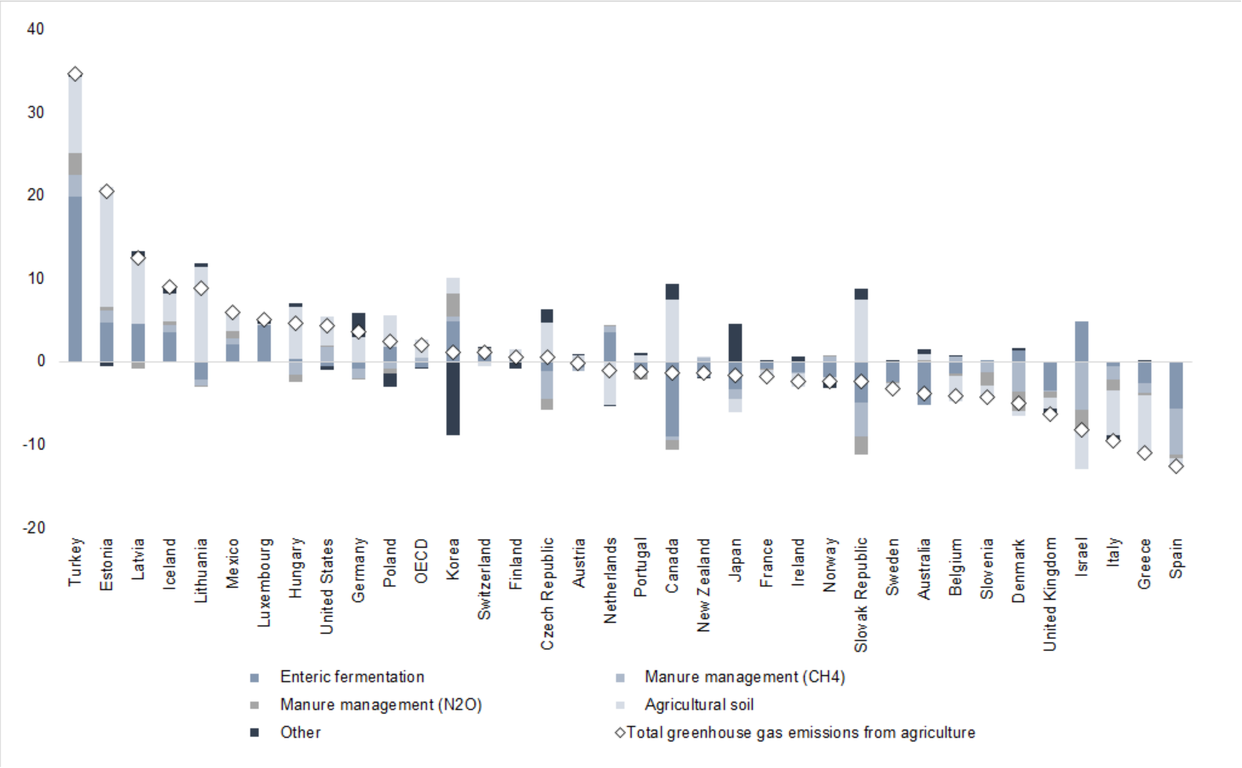
Note: Countries are ranked in descending order according to average annual percentage change 2003-05 to 2013-05. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.
1. Data for 1993-95 refer to the year 1996.
2. Data for 2013-15 refer to 2011-13.
Source: (OECD, 2018[1]).

The share of agriculture in total OECD GHG emissions was 9% in 2013-15. The relative contribution of agriculture in the total of national GHG emissions varies across countries, with six countries having a share 15% or higher in 2013-15 (**Denmark, France, Ireland, Latvia, Lithuania** and **New Zealand**), although the contribution of these countries to the total OECD agricultural GHG emissions was low except for **France**, whose share is 5.7%. The EU15 and the United States accounted together for 66% of OECD agricultural GHG emissions in 2013-15.

Higher agricultural soils emissions explain most of the increase in GHG emissions in OECD countries during the period 2003-15 (Figure 2.2). With the exception of **Iceland**, **Luxembourg**, **Mexico**, **Switzerland** and **Turkey**, agricultural soil emissions explain more than 50% of the raise in GHG emissions in countries that experienced an increase in GHG emissions in the period 2003-15. In the OECD area, the only GHG source that declined in the 2003-15 period was enteric fermentation; the rest, i.e., manure management, agricultural soils and others, increased. For most countries that decreased their GHG emissions in the period 2003-15, enteric fermentation explains more than 50% of the decline.

Figure 2.2. Agricultural soils emissions drive GHG emissions increase

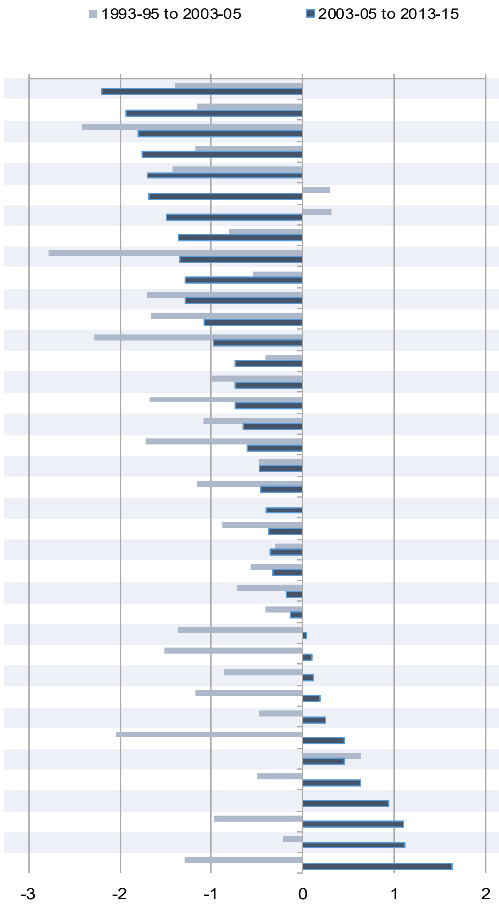
% change in GHG emissions from 2003-05 to 2013-15



Source: (OECD, 2018[1]).

Emissions intensities in OECD countries kept declining in the period 2003-15, but at a lower speed than in the period 1993-2005. Emissions intensities were 2 kg of CO_2e/USD in 1993-95, 1.8 kg of CO_2e/USD in 2003-05 and 1.7 kg of CO_2e/USD in 2013-15 (Figure 2.3). The top five countries that saw the largest decreases in emissions intensities from 2003 to 2015 were Australia, Israel, **Chile**, **New Zealand** and **Spain**. While in the period 1993-2005 only five countries, **Belgium**, **Latvia**, **Luxembourg**, **Japan** and the **United Kingdom**, increased their intensities, from 2003 to 2015, twelve countries did. Moreover, four of the top five largest GHG emitters in the OECD area, **France**, **Germany**, **Mexico** and the **United States** slowed the rate of decline in intensities in the period 2003-15; **Turkey**, the remaining country in the top five, even increased its emissions intensity at a rate of 0.4% per year.

Figure 2.3. GHG emissions intensity keeps declining in OECD countries



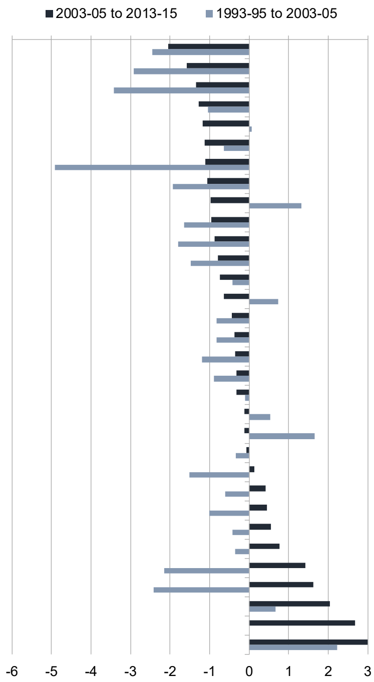
	Average			Change in agricultural GHG emissions intensity	
	Kilogram, CO_2 equivalent/ US$			Average annual % change	
	1993-95	2003-05	2013-15	1993-95 to 2003-05	2003-05 to 2013-15
Australia	3.35	2.91	2.33	-1.4	-2.2
Israel[1]	0.69	0.62	0.51	-1.2	-1.9
Chile[2]	3.18	2.49	2.16	-2.4	-1.8
New Zealand	5.41	4.80	4.03	-1.2	-1.8
Spain	1.09	0.95	0.80	-1.4	-1.7
Latvia	3.23	3.32	2.80	0.3	-1.69
United Kingdom	2.01	2.07	1.78	0.3	-1.5
Estonia	2.23	2.06	1.80	-0.8	-1.36
Mexico	3.82	2.88	2.51	-2.8	-1.3
Canada	2.49	2.36	2.07	-0.5	-1.29
Netherlands	1.49	1.26	1.11	-1.7	-1.3
Lithuania	3.12	2.64	2.37	-1.7	-1.1
Iceland	2.59	2.06	1.87	-2.3	-1.0
Norway	1.73	1.66	1.54	-0.4	-0.74
United States	2.72	2.46	2.28	-1.0	-0.7
Denmark	1.71	1.44	1.34	-1.7	-0.7
OECD[3]	**2.01**	**1.80**	**1.69**	**-1.1**	**-0.7**
Poland	2.18	1.84	1.73	-1.7	-0.6
Ireland	3.46	3.30	3.15	-0.5	-0.5
Germany	1.78	1.59	1.52	-1.2	-0.5
Belgium	..	1.21	1.16	0.0	-0.4
Portugal	1.16	1.06	1.02	-0.9	-0.37
Switzerland	1.00	0.97	0.94	-0.3	-0.4
EU15[3]	**1.67**	**1.58**	**1.53**	**-0.6**	**-0.3**
Sweden	2.17	2.02	1.99	-0.7	-0.2
France	1.44	1.38	1.37	-0.4	-0.1
Austria	1.49	1.30	1.30	-1.4	0.0
Korea	0.68	0.59	0.59	-1.5	0.1
Finland	2.53	2.32	2.34	-0.9	0.1
Italy	0.76	0.68	0.69	-1.2	0.2
Greece	0.58	0.56	0.57	-0.5	0.2
Turkey	0.96	0.78	0.82	-2.0	0.45
Japan	0.39	0.41	0.43	0.6	0.5
Czech Republic	1.88	1.79	1.90	-0.5	0.62
Luxembourg	..	2.52	2.76	0.0	0.9
Slovenia	2.24	2.03	2.27	-1.0	1.10
Hungary	1.08	1.06	1.18	-0.2	1.1
Slovak Republic	1.63	1.43	1.68	-1.3	1.6

Note: Countries are ranked in descending order according to average annual percentage change 2003-05 to 2013-05.
1. Data for 1993-95 refer to the year 1996.
2. Data for 2013-15 refer to 2011-13.
3. OECD and EU15 do not include Belgium and Luxembourg for the period 1993-95.
Source: Greenhouse gas emissions were obtained from (OECD, 2018[1]) and Gross Production Value from (FAOSTAT, 2018[14]).

2.2. Ammonia emissions kept declining in OECD countries

Ammonia emissions in the OECD region decreased in the period 2003-15 but at a slower speed than they did in the period 1993-2005. While a majority of countries decreased their emissions in the most recent period of analysis, countries such as **Austria**, **Estonia**, **Germany**, **Iceland**, **Latvia**, **Luxembourg** and **Switzerland** reversed their trends and increased their emissions in the period 2003-15 (Figure 2.4).

Figure 2.4. Ammonia emissions declining in OECD countries



	Average (thousand tonnes)			Average annual % change		Total ammonia emissions 2013-15[3] from all sources (thousand tonnes)	Agricultural % share in total ammonia emissions 2013-15
	1993-95[1]	2003-05	2013-15[2]	1993-95 to 2003-05	2003-05 to 2013-15		
Netherlands	243	137	107	-5.6	-2.4	124	86
Denmark	110	86	70	-2.4	-2.0	74	94
Slovak Republic	47	35	30	-2.9	-1.6	31	96
Czech Republic	106	75	65	-3.4	-1.3	72	90
Italy	437	394	346	-1.0	-1.3	371	93
Hungary	84	84	75	0.1	-1.2	84	89
Greece	65	61	55	-0.6	-1.1	60	91
Belgium	120	72	65	-4.9	-1.1	69	94
Lithuania	42	35	31	-1.9	-1.1	35	90
Spain	411	469	425	1.3	-1.0	466	91
Portugal	57	49	44	-1.6	-1.0	55	80
Poland	343	286	262	-1.8	-0.9	270	97
United States[4]	3 560	3 068	2 833	-1.5	-0.8	3 147	90
Slovenia	18	17	16	-0.4	-0.7	18	90
Finland	29	31	29	0.7	-0.6	32	90
EU15	**3 198**	**2 942**	**2 816**	**-0.8**	**-0.4**	**3 047**	**92**
Sweden	54	50	48	-0.8	-0.4	54	88
United Kingdom	276	245	236	-1.2	-0.4	273	86
OECD[5]	**8 508**	**7 777**	**7 525**	**-0.9**	**-0.3**	**8 272**	**91**
Ireland	112	111	108	-0.1	-0.3	109	99
Norway	25	27	26	0.5	-0.1	28	93
Canada	397	468	462	1.7	-0.1	494	94
France	610	590	586	-0.3	-0.1	621	94
Switzerland	61	53	53	-1.5	0.1	58	93
Austria	64	60	63	-0.6	0.4	67	94
Luxembourg	6	6	6	-1.0	0.4	6	95
Iceland	5	5	5	-0.4	0.5	5	98
Germany	604	583	630	-0.3	0.8	664	95
Estonia	12	9	11	-2.1	1.4	12	89
Latvia	15	12	14	-2.4	1.6	16	84
Turkey	453	484	593	0.7	2.0	658	90
Israel		13	17	n.a.	2.7		
Korea	143	178	233	2.2	3.0	296	79

Note: Countries are ranked in descending order according to average annual percentage change 2003-05 to 2013-05.

1. For Korea, 1990 data replace 1993-95 average.
2. For Korea, total emissions data for years 2012-4 replaces 2013-15 data.
3. For Korea, agricultural ammonia emissions data for years 2012-4 replaces 2013-15 data.
4. Data for agricultural ammonia emissions have been estimated based on the ratio agricultural ammonia/total ammonia emissions using the share 90% as recommended by USEPA.
5. Due to unavailable data, OECD average does not include Australia, Chile, Israel, Japan, Mexico and New Zealand.

Source: (OECD, 2018[1]).

International agreements to reduce emissions have been critical for reducing ammonia emissions. The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (GP) sets national ceilings for 2010/2020 for four major pollutants: sulphur (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs) and ammonia (NH_3) (UNECE, 2018[16]). The ceilings were negotiated and agreed on the basis of scientific assessments of pollution effects and abatement options. The ceilings are more stringent for Parties whose emissions have a more severe environmental or health impact and whose emissions are relatively cheap to reduce (UNECE, 2018[16]).

To meet the targets at the national level, guidance documents adopted together with the Protocol provide a wide range of abatement techniques and measures as well as economic instruments for the reduction of emissions in relevant sectors. In the case of agriculture, the Protocol establishes that, within a year of the entry into force of the Protocol, signatory Parties need to take the following measures (United Nations, 2013[17]): 1) establish, publish and disseminate an advisory code of good agricultural practice to control ammonia emissions; 2) take steps to limit ammonia emissions from the use of solid fertilisers based on urea and prohibit the use of ammonium carbinate fertilisers, 3) ensure that low-emissions slurry application techniques are used and that solid manure applied to land to be ploughed shall be incorporated within at least 24 hours of spreading, 4) for new slurry stores on large pig and poultry farms, use low-emissions storage systems and, for existing slurry stores on large pig and poultry farms, achieve emissions reductions of 40%; 5) use, for new animal housing on large pig and poultry farms, housing systems which have been shown to reduce emissions by 20%.

Specific abatement guidelines to implement the aforementioned measures have been disseminated by the Executive Body to the Convention on Long-range Transboundary Air Pollution. The first set of guidelines was published in 1999 and has been updated twice since then, as new evidence and technologies are available. The most recently updated guidelines include abatement recommendations pertaining to the following (UNECE, 2014[18]): a) nitrogen management, taking into account the whole N cycle; b) livestock feeding strategies; c) animal housing techniques; d) manure storage techniques; e) manure application techniques; f) fertiliser application techniques; g) other measures related to agricultural N; and h) measures related to non-agricultural and stationary sources. Abatement strategies are presented with their potential abatement potential and their associated costs. Optimised land application of slurry and improved livestock feeding strategies tend to be the most cost-effective practices (United Nations Economic Commission for Europe, 2015[19]). Communicating practical information to farmers through guidelines has also being important to spread adoption of such practices (Defra, 2018[20]; UNECE, 2014[18]).

In May 2012, the UN Economic Commission for Europe agreed on the amendments to the Protocol and set up new national emission reduction commitments for main air pollutants to be achieved in 2020 and beyond (Table 2.1).

Table 2.1. Ammonia emissions reduction commitments under the Gothenburg Protocol

Party	Emission levels 2005 in thousands of tonnes of NH_3	Reduction from 2005 level (%)
Austria	63	1
Belarus	136	7
Belgium	71	2
Bulgaria	60	3
Croatia	40	1
Cyprus	5.8	10
Czech Republic	82	7
Denmark	83	24
Estonia	9.8	1
Finland	39	20
France	661	4
Germany	573	5
Greece	68	7
Hungary	80	10
Ireland	109	1
Italy	416	5
Latvia	16	1
Lithuania	39	10
Luxembourg	5	1
Malta	1.6	4
Netherlands	141	13
Norway	23	8
Poland	270	1
Portugal	50	7
Romania	199	13
Slovakia	29	15
Slovenia	18	1
Spain	365	3
Sweden	55	15
Switzerland	64	8
United Kingdom of Great Britain and Northern Ireland	307	8
European Union	3813	6

Note: For Spain, figures apply to the continental European territory.

1. Note by Turkey: The information in this document with reference to “Cyprus” relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the “Cyprus issue”.

2. Note by all European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Source: Annex II of the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution (United Nations, 2013[17]).

3. Highly productive countries may be reaching a levelling-off point reducing their emission intensities

To reach the goal of keeping global temperature rise below 2 degrees Celsius this century while maintaining economic growth, countries will need to reduce the emissions per unit of output (emissions intensities) in all sectors of the economy. The agricultural sector is no exception, where lowering emissions has to be accompanied by output expansion to satiate increasing food demand from a growing and wealthier population; failing to do that could lead to price hikes and political unrest in certain regions of the world. In the past, productivity growth and agricultural area expansion have driven food supply growth (Foley et al., 2011[21]). Unfolding the relationship between productivity growth and emissions intensity can help understand both the present and future role of productivity growth in tackling global warming.

In OECD countries, the growth of agricultural labour productivity goes along with emission intensity reductions up to a point, after which emission intensities do not decrease and could even increase when labour productivity increases. Using the greenhouse gas emissions data from the OECD agri-environmental indicators (OECD, 2018[1]) in combination with farm labour statistics from USDA (USDA, 2018[22]) and data on agricultural gross production from FAO (FAOSTAT, 2018[14]), Figure 3.1 plots the estimated[1] association between agricultural labour productivity and a) GHG, b) CH_4 and c) N_2O and emissions intensities. Emission intensity is defined as in Box 2.1 and agricultural labour productivity is defined as the ratio of gross production value to the number of workers economically active in agriculture. While this indicator is only a partial productivity measure as it excludes capital and other variable inputs, it is an appropriate indicator to reflect the long-term evolution of the sector and its structural transformation as it is less responsive to changes in variable inputs (Coderoni and Esposti, 2014[23]).[2] The data used for producing the figures represents 33 countries[3] during the period 1990-2015.

For GHG emissions in total, CH_4 and N_2O the point at which the relationship between emission intensities and labour productivity levels off is found at a level of USD 20 000/worker (Figure 3.1). In 2015, the median labour productivity in OECD

---

[1] See Annex A for a detailed description of the method used for the estimation.

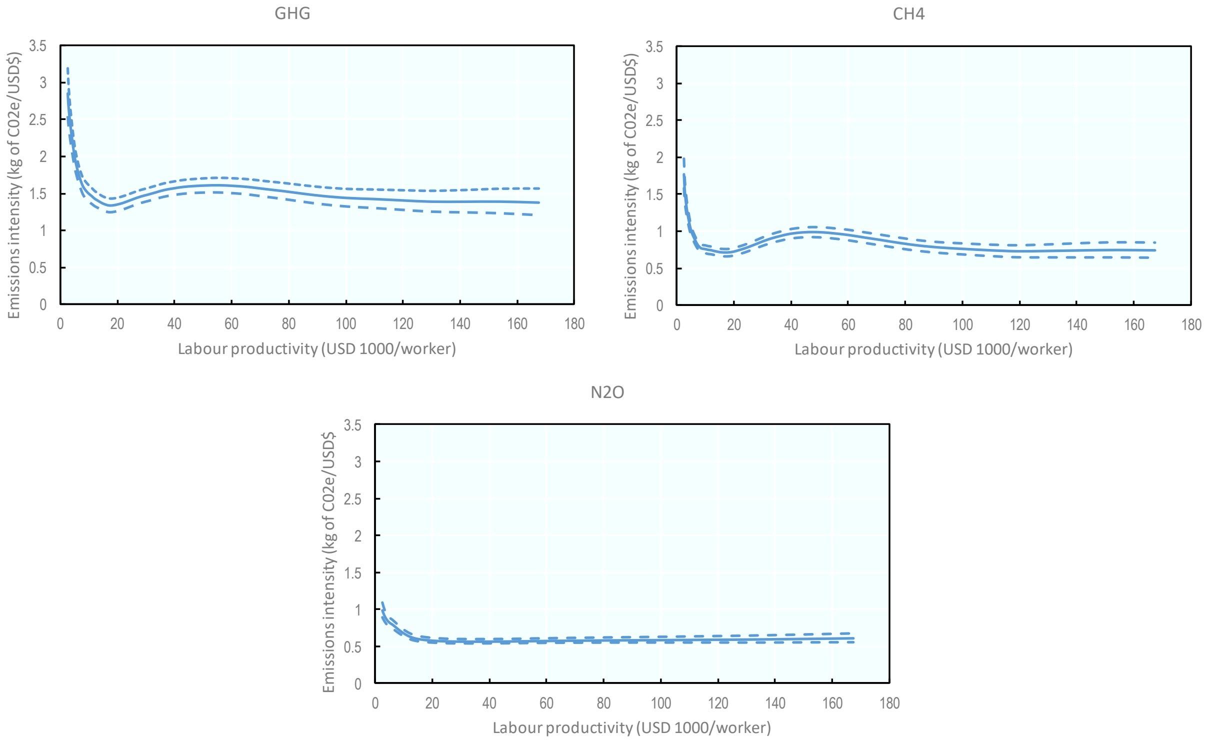
[2] An alternative productivity indicator is the Total Factor Productivity that is produced by USDA. The TFP is an index that measures agricultural productivity in relation to a baseline year, so its interpretation is not straightforward and comparisons between the levels of different countries are meaningless. Another drawback for its use in this setting is that it includes variable inputs such as fertiliser and feed which are subject to short-term drivers such as weather and market shocks that are not necessarily relevant to the structural transformation of agriculture (Coderoni and Esposti, 2014[23]). Moreover, the correlation between TFP and labour productivity in our dataset is relatively large (0.7), indicating that although labour productivity may be a partial measure of productivity, it is a good proxy for total factor productivity.

[3] Australia, Austria, Belgium-Luxembourg (joint due to lack of data availability), Canada, Chile, Czech Republic-Slovakia (joint due to data availability), Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

countries was USD 44 700/worker, indicating that most countries are already beyond such point. This may suggest that further improvements in labour productivity will not necessarily translate into reductions in emission intensities and could even increase them. Therefore, productivity improvements may not be enough to improve emissions intensities; policy action addressing emissions may be needed to reduce emissions per unit of output.

For GHG and CH_4, the relationship between emissions intensities and labour productivity is nonlinear and after a USD 20 000/worker level in productivity, emissions intensities increase up to a given point (USD 54 000/worker) after which emissions intensities tend to decrease again. The shape of the relationship between N_2O emissions intensities and labour productivity is relatively flatter compared to GHG and CH_4, and, for N_2O emissions intensities, productivity improvements beyond the levelling-off point do not seem to affect emissions intensities. This more moderated relationship may be driven by the fact that reductions in N_2O emissions intensities are mostly driven by reduced use of fertilisers, which may not necessarily translate into a labour force reduction.

Figure 3.1. GHG emissions intensities decrease with labour productivity up to a tipping point



Note: All variables were transformed to non-logged values. Dash lines show the corresponding 95% confidence intervals. Source: Gross Production Value was obtained from FAOSTAT (FAOSTAT, 2018[14]), measured in constant 2004-2006 million USD. Agricultural labour was obtained from USDA (USDA, 2018[22]), measured in 1 000 workers.

Source: Greenhouse gas emissions were obtained from the OECD Agri-environmental Indicators database (OECD, 2018[1]).

The negative nonlinear relationship between emissions intensities and labour productivity is confirmed via a parametric regression analysis.[4] Increases in labour productivity are accompanied by emissions intensities declines (Table 3.1), but this negative relationship becomes less negative as productivity increases (the quadratic term is positive), reaching a turning point (the cubic term is negative) after which the relationship can become negative again. Those sign conditions are consistent with Figure 3.1. There is also persistence in emissions intensities: past emission intensities tend to define current intensities (*Lagged Emissions Intensity* coefficient is positive and statistically significant).

Table 3.1. Negative non-linear relationships between productivity and emissions intensities

	Dependent variables		
	GHG intensity	CH_4 intensity	N_2O intensity
Lagged Emissions Intensity	0.678***	0.672***	0.729***
	(0.03)	(0.029)	(0.028)
Labour productivity	-0.369***	-0.416***	-0.250***
	(0.079)	(0.086)	(0.085)
Labour productivity Squared	0.110***	0.108***	0.085***
	(0.027)	(0.029)	(0.03)
Labour productivity Cubic	-0.012***	-0.010***	-0.010***
	(0.003)	(0.003)	(0.003)
Trend	-0.001	-0.001	0
	(0.001)	(0.001)	(0.001)
Observations	758	760	760
Sargan test of over-identification	618.6122	653.423	622.941
	(0.73)	(0.379)	(0.846)

Note: Due to data availability, Slovenia is excluded. Belgium and Luxembourg, and the Czech Republic and the Slovak Republic are combined, respectively. Difference in observations between GHG and others comes from a lack of data on GHG emission in 2014 and 2015 for Chile. All variables were transformed into logarithms. Year dummies were included. Coefficients were estimated using Arellano-Bond one-step GMM estimation and standard errors are shown in parentheses. *, ** and *** represent statistically significant coefficients at the 10%, 5% and 1% levels, respectively.

Source: Greenhouse gas emissions were obtained from the OECD Agri-environmental Indicators database (OECD, 2018[1]).

---

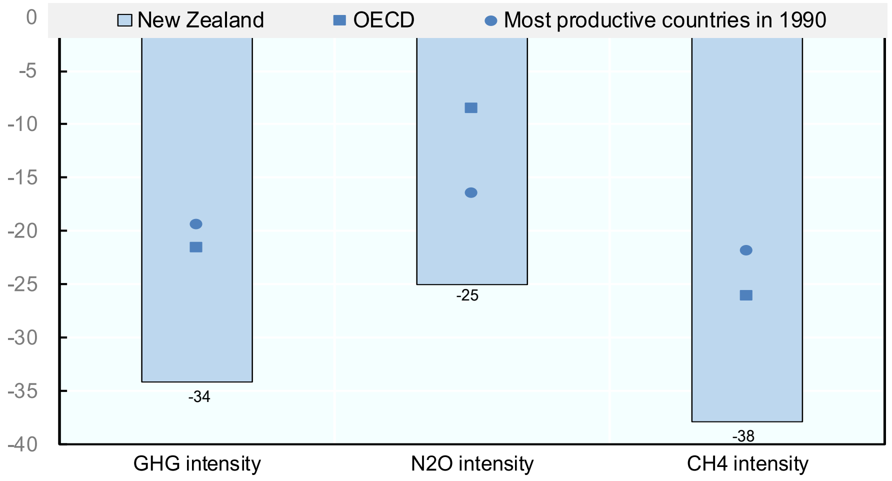
[4] See Annex A for a detailed description of the method used for the estimation.

4. Investing in research and development and technology transfer drives New Zealand's emissions intensity reductions

New Zealand registered simultaneously one of the largest declines in greenhouse gas emissions per value of production in the OECD area, agricultural production growth and a sharp reduction in agricultural land. This set of events are more notable considering the large share that agriculture has on the economy (7%) and its specialisation in livestock production (especially dairy products and sheep meat) (OECD, 2018[24]), a sector characterised by its high emissions intensities. From 1990 to 2015, the intensity of New Zealand's agricultural GHG emissions decreased 34%, a negative rate higher than both OECD average rate (-22%) and the average top 10 countries with the largest values of agricultural labour productivity (excluding New Zealand) in 1990 (-19%) (Figure 4.1). Emission intensity reductions were achieved in both N_2O and CH_4 and, in both cases, were larger than OECD and most productive countries as of 1990. As measured on a per unit of product (kg of meat or milk), emissions intensities have declined 20% in New Zealand's pastoral agriculture (Parliamentary Commissioner for the Environment, 2016[25]). While total GHG emissions from agriculture increased 13% from 1990 to 2015, they would have been higher without emission intensities improvements (Ministry for the Environment, 2018[26]).

Figure 4.1. New Zealand's has remarkably reduced its emissions intensities

% change in emissions intensities 1990-2015



Note: Emission intensity is calculated as the ratio of greenhouse gas emissions to agricultural gross production value.

Source: GHG emissions were obtained from the OECD Agri-environmental Indicators Database (OECD, 2018[1]) and agricultural gross production value was obtained from FAOSTAT (FAOSTAT, 2018[14]).

These achievements are mainly explained by 1) the adoption of policies focused on research and development, particularly targeting farm profitability, productivity and emissions intensity reductions, 2) changes in the production mix of animal species and 3) low levels of distortionary support to agriculture (Henderson and Lankoski, forthcoming 2019[27]). From 1990 to 2016, New Zealand became more specialised in the production of dairy products. The population of sheep decreased by 52.3% and non-dairy livestock by 23.1%, while the size of the dairy herd increased by 92.4% (Ministry for the Environment, 2018[26]). Land use for sheep, beef and deer grazing decreased by 31.6%, whereas it increased by 71.7% for dairy grazing (Ministry for the Environment, 2018[26]). New Zealand's support to farmers is one of the lowest in the OECD area (below 1% of gross farm receipts) and agricultural policies focus on key general services such as agricultural knowledge, innovation and biosecurity, representing more than 70% of total support to agriculture (OECD, 2018[28]).

The government strongly supports innovation and technology transfer to reduce greenhouse gas emissions of the agricultural sector; it is also an international leader supporting research efforts in the topic. New Zealand has established dedicated institutions and R&D funding for reducing the greenhouse gas emissions of the agricultural sector such as the New Zealand Agricultural Greenhouse Gas Research Centre,[5] the Pastoral Greenhouse Gas Research Consortium,[6] and the Sustainable Farming Fund. In addition, New Zealand leads the Global Research Alliance on Agricultural Greenhouse Gases[7] which aims to share knowledge and expertise on reducing GHG emissions across 56 member countries. In New Zealand, R&D institutions work closely with farmers and industry to develop mitigation technologies and options that can, at the same time, be economically attractive (Ministry for the Environment, 2017[29]); they also organise workshops, meetings and presentations to relevant stakeholders (Lissaman, Casey and Rowarth, 2013[30]; Kerr et al., 2013[31]; Payne, Turner and Percy, 2018[32]). Since 1990, New Zealand has reduced the emissions intensities of the sector mainly by improving pasture management, nutrient management, animal selection and genetics and animal health.

Urease inhibitors have been used as a mitigation technology since 2001 and their adoption rates are on the rise since 2014. In New Zealand, urea is the main type of nitrogen fertiliser applied to pastures; urease inhibitors restrict the action of the enzyme urease which produces ammonia emissions (Ministry for the Environment, 2018[26]). Inhibitors reduce by half the fraction of nitrogen from synthetic nitrogen fertiliser that volatilises as NH_3 (Saggar et al., 2013[33]). Urease inhibitors adoption rates have been relatively low but, since 2014, they have increased. The percentage of urea fertiliser that includes urease inhibitors sold from 2001 to 2013 in New Zealand was 6%. In 2014, the percentage increased sharply to 20% and, from 2014 to 2016, it has been 21% on average.

Looking ahead, New Zealand has clear reduction targets both internationally and nationally. It sets a target at -5 % below 1990 levels by 2020 under the UNFCCC and at -11% below 1990 levels by 2030 under the Paris Agreement. In 2018, the government proposed the Zero Carbon Bill that sets the national gazetted target at -50% below 1990 levels by 2050. There are currently ongoing discussions to define the future target under the Zero Carbon Bill policy.

In order to attain those goals, emissions reductions in the agricultural sector are expected to be attained by a combination of policies and technological improvements. The main policy instrument for reducing GHG emissions in New Zealand is the Emissions Trading Scheme (ETS). Under the ETS agriculture has reporting obligations but not surrender obligations. The New Zealand government has projected that improvements in emissions

---

[5] www.nzagrc.org.nz

[6] www.pggrc.co.nz

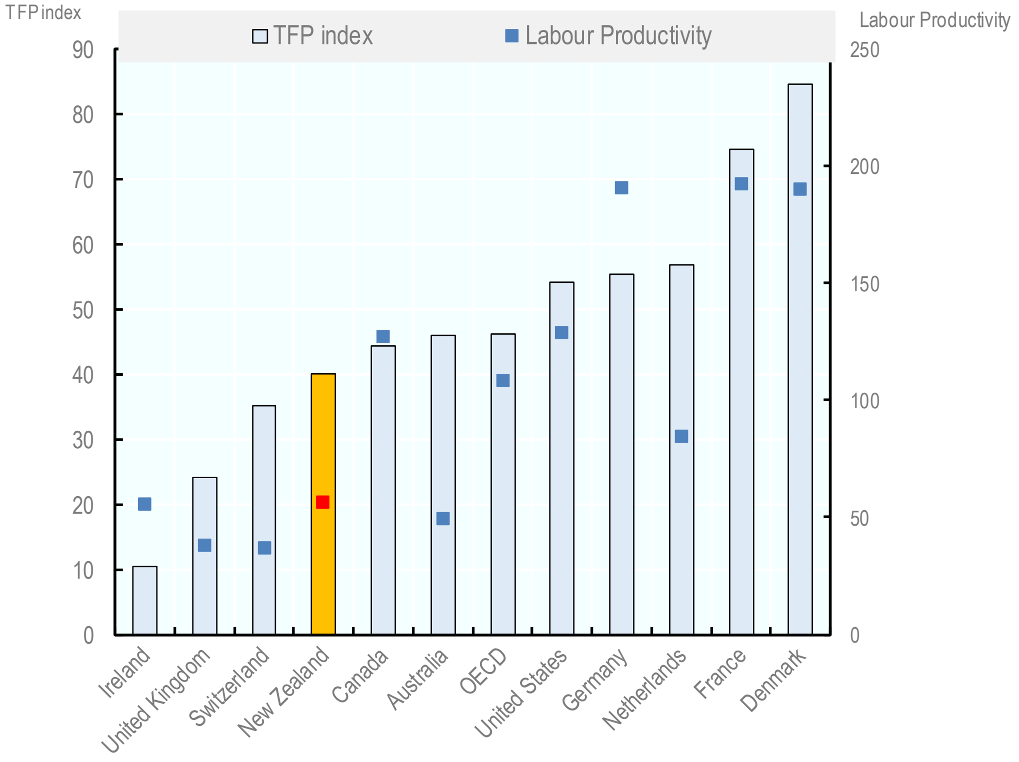
[7] www.globalresearchalliance.org

intensities will continue and that, in combination with the implementation of the National Policy Statement for Freshwater Management (the main policy to improve water quality) and government schemes to incentivise forestry, the agricultural sector could achieve a 4.8% reduction of the projected emissions compared to a scenario without policy interventions in the period 2016-30 (Ministry for the Environment, 2017[34]). Additional reductions (up to 10%) may be achieved by increasing the adoption of readily available technologies to reduce emissions, but relevant adoption barriers still remain: education levels, environmental awareness, risk aversion, trust in extension services, etc. (Ministry for Primary Industries, 2018[35]).

A key question is whether the observed negative trends of emissions intensities can be maintained without affecting productivity growth. In spite of outstanding achievements in emissions intensities reductions, productivity growth may be an area of concern. From 1990 to 2015, accumulated total factor productivity growth was 40% in New Zealand; such a rate is lower relative to the one that other highly productive countries achieved in the same period (50%) (Figure 4.2). If measured by gross production value per worker, New Zealand ranks 7th (56% increase) in terms of productivity growth among the top 10 most productive countries in 1990 and that rate was almost half the average for OECD countries (109%) (Figure 4.2).

Figure 4.2. Agricultural productivity growth has been modest in New Zealand relative to highly productive countries in 1990

% growth 1990-2015



Note: Agricultural productivity growth is calculated as the ratio of agricultural gross production value to number of workers in the agricultural sector.
Source: Agricultural gross production value was obtained from FAOSTAT (FAOSTAT, 2018[14]), labour and TFP indices were obtained from USDA (USDA, 2018[22]).

References

Arellano, M. and S. Bond (1991), “Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations”, *The Review of Economic Studies*, Vol. 58/2, p. 277, http://dx.doi.org/10.2307/2297968. [42]

Barros, V. et al. (2015), “Climate change in Argentina: Trends, projections, impacts and adaptation”, *Wiley Interdisciplinary Reviews: Climate Change*, Vol. 6/2, pp. 151-169, http://dx.doi.org/10.1002/wcc.316. [6]

Bouwman, A. et al. (1997), “A global high-resolution emission inventory for ammonia”, *Global Biogeochemical Cycles*, Vol. 11/4, pp. 561-587, http://dx.doi.org/10.1029/97GB02266. [8]

CEIP (2019), *1999 Gothenburg protocol under the LRTAP Convention*, http://www.ceip.at/ms/ceip_home1/ceip_home/gothenburg_protocol/. [43]

Choi, I. (2001), “Unit root tests for panel data”, *Journal of International Money and Finance*, Vol. 20/2, pp. 249-272, http://dx.doi.org/10.1016/S0261-5606(00)00048-6. [38]

Coderoni, S. and R. Esposti (2014), “Is There a Long-Term Relationship Between Agricultural GHG Emissions and Productivity Growth? A Dynamic Panel Data Approach”, *Environmental and Resource Economics*, Vol. 58/2, pp. 273-302, http://dx.doi.org/10.1007/s10640-013-9703-6. [23]

Defra (2018), *Code of Good Agricultural Practice (COGAP) for Reducing Ammonia Emissions*, http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/ (accessed on 22 January 2019). [20]

Edenhofer, O. et al. (eds.) (2014), *Agriculture, forestry and other land use (AFOLU)*, Cambridge University Press. [3]

FAOSTAT (2018), *Value of Agricultural Production*, http://www.fao.org/faostat/en/#data/QV/metadata. [14]

Foley, J. et al. (2011), “Solutions for a cultivated planet”, *Nature*, Vol. 478, pp. 337–342, http://dx.doi.org/10.1038/nature10452. [21]

Henderson, B. and J. Lankoski (forthcoming 2019), *Evaluating the environmental impact of agicultural policies*. [27]

Im, K., M. Pesaran and Y. Shin (2003), “Testing for unit roots in heterogeneous panels”, *Journal of Econometrics*, Vol. 115/1, pp. 53-74, http://dx.doi.org/10.1016/S0304-4076(03)00092-7. [40]

IPCC (2014), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*. [2]

Kerr, S. et al. (2013), *Tackling Agricultural Emissions Potential Leadership from a Small Country*, http://www.motu.org.nz/publications/motu-notes (accessed on 21 January 2019). [31]

Lissaman, W., M. Casey and J. Rowarth (2013), *Innovation and technology uptake on farm*, New Zealand Grassland Association, https://www.grassland.org.nz/publications/nzgrassland_publication_2523.pdf (accessed on 24 January 2019). [30]

Ministry for Primary Industries (2018), *Report of the Biological Emissions Reference Group*, https://www.mpi.govt.nz/. [35]

Ministry for the Environment (2018), *New Zealand's Greenhouse Gas Inventory 1990–2016*, Ministry for the Environment , Wellington, New Zealand, http://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/National%20GHG%20Inventory%20Report%201990-2016-final.pdf (accessed on 17 January 2019). [26]

Ministry for the Environment (2017), *New Zealand's Seventh National Communication - Fulfilling reporting requirements under the United Nations Framework convention on Climate change and the Kyoto Protocol*, http://dx.doi.org/www.mfe.govt.nz. [34]

Ministry for the Environment (2017), *The Structure of Agricultural greenhouse gas research funding in New Zealand*, https://www.nzagrc.org.nz/. [29]

Morán, M. et al. (2016), "Ammonia agriculture emissions: From EMEP to a high resolution inventory", *Atmospheric Pollution Research*, Vol. 7/5, pp. 786-798, http://dx.doi.org/10.1016/j.apr.2016.04.001. [15]

Murgida, A. et al. (2014), *Evaluación de impactos del cambio climático sobre la producción agrícola en la Argentina*, CEPAL, https://repositorio.cepal.org/bitstream/handle/11362/37197/1/LCL3770_es.pdf (accessed on 6 June 2018). [7]

Nguyen Van, P. (2005), "Distribution Dynamics of CO2 Emissions", *Environmental & Resource Economics*, Vol. 32/4, pp. 495-508, http://dx.doi.org/10.1007/s10640-005-7687-6. [36]

OECD (2018), *Agricultural Policy Monitoring and Evaluation 2018*, OECD Publishing, Paris, https://dx.doi.org/10.1787/agr_pol-2018-en. [28]

OECD (2018), *Agri-environmental indicators*, http://www.oecd.org/tad/sustainable-agriculture/agri-environmentalindicators.htm. [1]

OECD (2018), *Chapter 17. New Zealand Support to agriculture*, OECD, Paris, http://dx.doi.org/10.1787/agr-pcse-data-en. [24]

OECD (2018), *Human Acceleration of the Nitrogen Cycle: Managing Risks and Uncertainty*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264307438-en. [12]

OECD (2015), *The Economic Consequences of Climate Change*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264235410-en. [5]

OECD (2008), *Environmental Performance of Agriculture in OECD countries since 1990*, http://dx.doi.org/www.oecd.org/tad/env/indicators. [11]

Ordás Criado, C. (2008), "Temporal and Spatial Homogeneity in Air Pollutants Panel EKC Estimations Two Nonparametric Tests Applied to Spanish Provinces", *Environ Resource Econ*, Vol. 40, pp. 265-283, http://dx.doi.org/10.1007/s10640-007-9152-1. [37]

Parliamentary Commissioner for the Environment (2016), *Climate change and agriculture: understanding the biological greehouse gases*, http://dx.doi.org/www.pce.parliament.nz. [25]

Payne, P., J. Turner and H. Percy (2018), *A Review of the SLMACC Technology Transfer Projects*, MPI, Wellington, http://www.mpi.govt.nz/news-and-resources/publications/. [32]

Pedroni, P. (1999), "Critical Values for Cointegration Tests in Heterogeneous Panels with Multiple Regressors", *Oxford Bulletin of Economics and Statistics*, Vol. 61/s1, pp. 653-670, http://dx.doi.org/10.1111/1468-0084.0610s1653. [41]

Perman, R. and D. Stern (2003), "Evidence from panel unit root and cointegration tests that the Environmental Kuznets Curve does not exist", *Australian Journal of Agricultural and Resource Economics*, Vol. 47/3, pp. 325-347, http://dx.doi.org/10.1111/1467-8489.00216. [39]

Saggar, S. et al. (2013), "Quantification of reductions in ammonia emissions from fertiliser urea and animal urine in grazed pastures with urease inhibitors for agriculture inventory: New Zealand as a case study", *Science of the Total Environment*, Vol. 465, pp. 136-146, http://dx.doi.org/10.1016/j.scitotenv.2012.07.088. [33]

Tubiello, F. et al. (2013), "The FAOSTAT database of greenhouse gas emissions from agriculture", *Environmental Research Letters*, Vol. 8, http://dx.doi.org/10.1088/1748-9326/8/1/015009. [4]

UNECE (2018), *Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, http://www.unece.org/env/lrtap/multi_h1.html. [16]

UNECE (2014), *Guidance document on preventing and abating ammonia emissions from agricultural sources Summary*, UNECE, http://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_120_ENG.pdf (accessed on 23 January 2019). [18]

UNFCCC (2018), *National Inventory Submissions 2018*, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018. [13]

United Nations (2013), *1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution, as amended on 4 May 2012*. [17]

United Nations Economic Commission for Europe (2015), *Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions*. [19]

USDA (2018), *International Agricultural productivity*, https://www.ers.usda.gov/data-products/international-agricultural-productivity. [22]

Xu, R. et al. (2019), “Global ammonia emissions from synthetic nitrogen fertilizer applications in agricultural systems: Empirical and process-based estimates and uncertainty”, *Global Change Biology*, Vol. 25, pp. 314–326, https://doi.org/10.1111/gcb.14499. [10]

Zhang, Y. et al. (2010), “Agricultural ammonia emissions inventory and spatial distribution in the North China Plain”, *Environmental Pollution*, Vol. 158/2, pp. 490-501, http://dx.doi.org/10.1016/j.envpol.2009.08.033. [9]

Annex A.

This annex provides further details on the analysis in Section 3. Table A.1 shows descriptive statistics of the data used, which includes 33 countries in the period 1990-2015.

Figure A.1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Labour productivity (USD1 000/worker)	828	34.867	28.320	2.614	167.456
GHG emission intensity (kg of CO_2e/USD)	880	1.841	0.987	0.374	5.856
N_2O emission intensity (kg of CO_2e/USD)	882	0.744	0.407	0.111	2.360
CH_4 emission intensity (kg of CO_2e/USD)	882	1.051	0.698	0.195	4.645

Source: Agricultural gross production value was obtained from FAOSTAT (FAOSTAT, 2018[14]), labour data were obtained from USDA (USDA, 2018[22]) and GHG emissions data from the OECD Agri-environmental Indicators Database (OECD, 2018[1]).

Figure 3.1 was estimated using non-parametric methods. Non-parametric methods are suitable for this analysis because they do not assume a particular shape of the relationship between the outcome and the covariates (Nguyen Van, 2005[36]; Ordás Criado, 2008[37]). The method consists on running a number of local regressions at different values of the covariates with an optimal bandwidth. The density of the outcome is estimated by using Epanechnikov Kernel function. A rule-of-thumb estimator selects the optimal bandwidth. Only two variables are used, agricultural labour productivity versus emission intensities (GHG, CH_4 and N_2O) to create the graphs in Figure 3.1.

$$e_{kit}^{GPV} = \alpha_i + \beta_{k1} p_{it}^{L} + \beta_{k2} (p_{it}^{L})^2 + \beta_{k3} (p_{it}^{L})^3 + t + u_{kit},$$

$$u_{kit} = \gamma_{ki} + \eta_{kit},$$

This model requires that variables are stationary or, at least, cointegrated, so that the relationship obtained in the parametric regression is not merely spurious. First, panel unit root tests are conducted to test for stationarity (Choi, 2001[38]; Perman and Stern, 2003[39]; Coderoni and Esposti, 2014[23]). Three variables, namely Labour productivity, GHG emission intensity, and CH_4 emission intensity, do not reject the null hypothesis of containing unit roots (hence are not stationary) even at 10% level; they become stationary when first differences are taken (Table 4.1).

Table 4.1. Unit root test

	Estimate	P-Value		Estimate	P-Value
Labour productivity (GPV/L)	-4.577	1.000	Δ Labour productivity GPV/L	46.563	0.000
GHG emission intensity	0.719	0.236	Δ GHG emission intensity	52.952	0.000
N_2O emission intensity	2.907	0.002	Δ N_2O emission intensity	49.162	0.000
CH_4 emission intensity	0.497	0.310	Δ CH4 emission intensity	55.931	0.000

Note: Fisher type augmented Dickey-Fuller tests (F-ADF) are conducted. Null hypothesis is containing unit roots in all panels and the alternative is at least one individual in the panel is stationary. We do not include a trend and one lag is used in the ADF regressions. In addition, Im-Pesaran-Shin test is performed (Im, Pesaran and Shin, 2003[40]) and indicates the similar results as F-ADF tests.

Provided those three variables have unit roots in levels, a cointegration tests is performed next to check for long-term relationships (Pedroni, 1999[41]). According to the results in Table 4.2, all the tests, except group ρ, are significant at the 5% level for both GHG and CH_4 emission intensities. Hence, there exists a cointegrating relationship between GHG and CH_4 emission intensities with first, second and third power of labour productivity.

Table 4.2. Cointegration test

	GHG emission intensity		CH_4 emission intensity	
Test statistics	Panel	Group	Panel	Group
v	3.003		2.726	
	(0.001)		(0.003)	
ρ	-2.591	-1.041	-1.708	-0.203
	(0.005)	(0.149)	(0.044)	(0.420)
t	-7.116	-8.414	-5.878	-7.201
	(0.000)	(0.000)	(0.000)	(0.000)
ADF	-4.727	-5.189	-3.353	-4.850
	(0.000)	(0.000)	(0.000)	(0.000)

Note: Data for 1996 and 2000 of Israel are excluded, as cointegration tests do not allow gaps. All statistics are distributed as N(0,1). Rejecting the null of no cointegration is one-sided. Panel *v* is non-parametric variance ratio statistic, ρ is non-parametric test statistic, *t* and ADF (augmented Dickey-Fuller) are parametric statistic. Time dummies included but not trend.

Given these results, the preferred model is a dynamic model as it can capture the processes of adjustment to the long-run equilibrium as indicated by the results of the cointegration test. The estimated model is the Arellano-Bond one-step GMM estimation (Arellano and Bond, 1991[42]). The dynamic model generally includes lagged dependent variables as explanatory variable as follows.

$$e_{kit}^{GPV} = \alpha_{ki} + \varphi_{ki} e_{ki,t-1}^{GPV} + \beta_{k1} p_{it}^{L} + \beta_{k2} (p_{it}^{L})^2 + \beta_{k3} (p_{it}^{L})^3 + trend + year + u_{kit},$$

where variables are indexed over the types of emission k, country i, and year t. The dependent variable e_{kit}^{GPV} is the log of emission intensity. The independent variables are the log of agricultural labour productivity p_{it}^{L} and its squared and cubed terms. α_{ki} is the intercept. $u_{kit} = v_i + \varepsilon_{kit}$ is the error term composed of a panel-level effects component (v_i) and an error term i.d.d. over the whole sample (ε_{kit}) and m is the maximum length of lag. A trend ($trend$) and year dummies ($year$) have also been included.

Arellano-Bond GMM uses instruments to deal with endogeneity between the lag of the dependent variable and the error term. We perform the one-step GMM estimation which assumes homoscedasticity on the disturbance term u_{kit}. For model specification, AR(2) test for serial correlation and Sargan test for over-identification.

Since autocorrelation of order 2 was not ruled out, for robustness check, results from a static random-effects model are displayed in Table A.1. Results support the nonlinear and negative relationship between labour productivity and emissions intensities.

Table A.1. Static model

	Dependent variable: Emission intensity		
	GHG	N_2O	CH_4
Labour productivity	-1.111***	-0.814*	-1.274***
	(0.279)	-0.445	(0.250)
Labour productivity Squared	0.353***	0.310**	0.357***
	(0.099)	-0.152	(0.086)
Labour productivity Cubic	-0.036***	-0.036**	-0.033***
	(0.011)	-0.017	(0.010)
Trend	0.001***	-0.004	0.004
	(0.000)	-0.01	(0.011)
Observations	826	828	828
Number of Countries	33	33	33
R-squared	0.562	0.343	0.609

Note: All variables were transformed into logarithms. Coefficients were estimated using a random effect model and robust standard errors are reported in parentheses. *, ** and *** represent statistically significant coefficients at the 1%, 5% and 10% levels, respectively. Year dummies are included.

Source: Gross Production Value was obtained from FAOSTAT (FAOSTAT, 2018[14])and agricultural labour was obtained from USDA (USDA, 2018[22]). Emissions data come from the OECD Agri-environmental Indicators database (OECD, 2018[1]).