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INTEGRATED APPROACHES FOR AGRICULTURAL SUSTAINABILITY AND PRODUCTIVITY ASSESSMENTS

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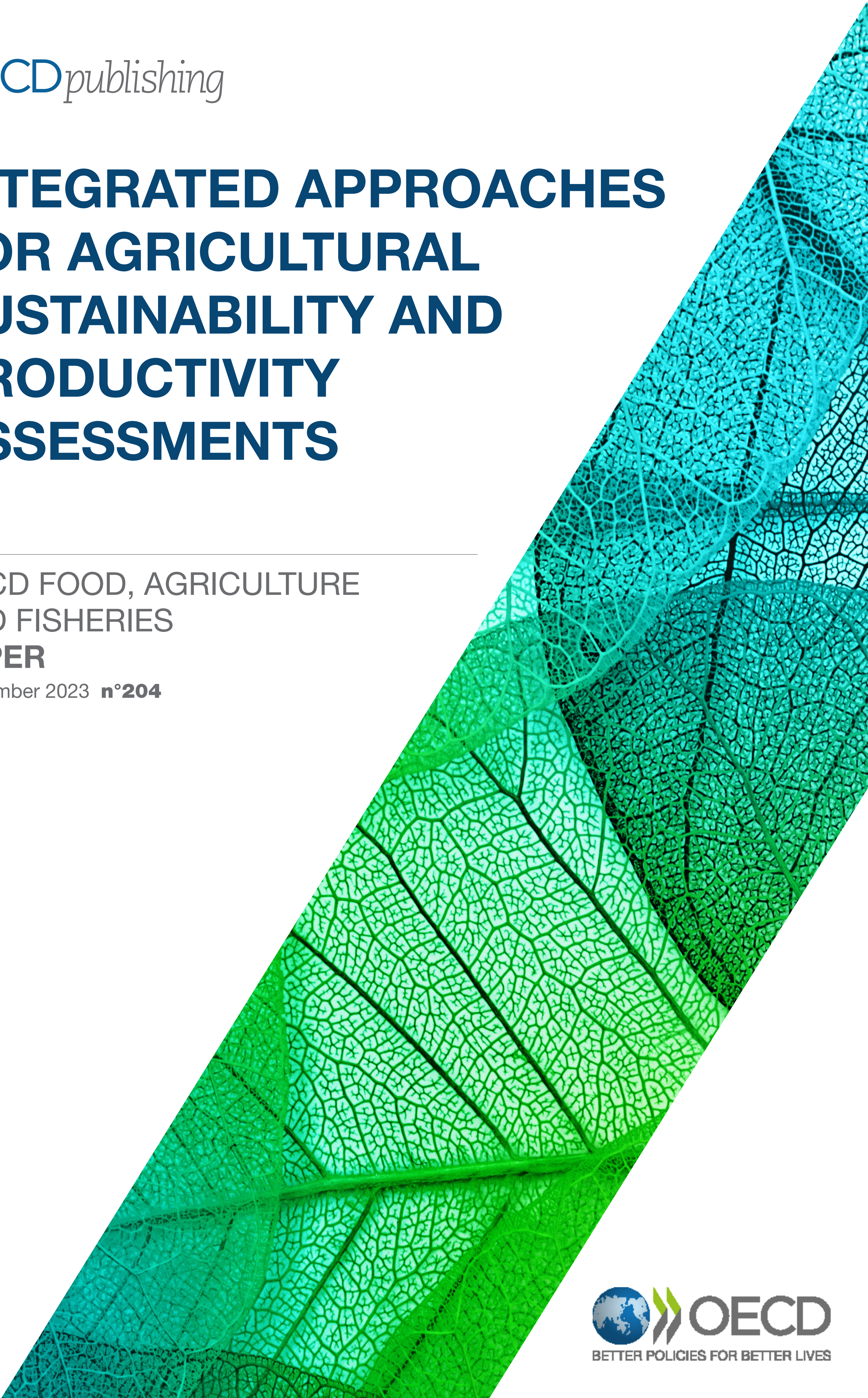

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Integrated Approaches for Agricultural Sustainability and Productivity Assessments

Ben Henderson and Jussi Lankoski

Increasing agricultural productivity growth sustainably can help to address the triple challenge of providing sufficient affordable and nutritious food for a growing global population, while supporting sector livelihoods and improving environmental outcomes. However, challenges remain in measuring environmentally sustainable productivity growth. This study uses alternative approaches to address these challenges and provides answers to the following questions: i) has Total Factor Productivity (TFP) growth coincided with improved environmental outcomes?; and ii) has the agricultural productivity and environmental performance of countries improved over time? While there is compelling evidence that TFP growth has helped countries to expand agricultural output and reduce greenhouse gas emissions per unit of output, these emissions increased in absolute terms for about half of the OECD countries assessed and nitrogen surpluses increased for about one-third. While these environmental impacts would have been larger if output had expanded in the absence of productivity growth, there is room to steer innovation in the sector in a more environmentally sustainable direction.

Key words Total factor productivity, agri-environmental indicators, greenhouse gas emissions, nutrient balances

JEL codes D24, Q01, Q56, Q10

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Key messages

- Increasing agricultural productivity growth sustainably is necessary to address the triple challenge of providing sufficient affordable and nutritious food for a growing global population, while supporting sector livelihoods and improving environmental outcomes. However, challenges remain in measuring concurrent progress across all of these dimensions, particularly regarding environmentally sustainable productivity growth.
- Given these concerns and the neglect of environmental externalities and natural resources in standard measures of total factor productivity (TFP), this study explores alternative approaches (applied to a sample of 33 OECD countries over 2006-2015) to provide answers to the following questions:
    - Has TFP growth coincided with improved environmental outcomes?
    - Has countries' performance with respect to both agricultural productivity and the environment improved over time?
- Regarding the first question, improved environmental outcomes have indeed coincided with TFP growth. About three-quarters of the sample countries have succeeded in reducing the greenhouse gas (GHG) emission intensity of their agricultural production, and all but two of these countries registered TFP growth).
- Simultaneous growth in output and lowering of GHG emissions (absolute decoupling) has mainly been achieved by countries with a TFP growth path that is dominated by reductions in input use. A reduction in animal numbers, in particular, has underpinned their emission reductions.
- In contrast, countries in which TFP growth is dominated by an expansion of output have lowered the GHG emission intensity of their output by increasing their emissions at a slower rate than output, but have not reduced their absolute GHG emissions from agriculture (relative decoupling).
- To answer the second question, simple composite indicators were constructed based on the concepts of weak environment-productivity growth (WEP) and strong environment-productivity growth (SEP). These combine both annual rates of growth of TFP and changes in two selected agri-environmental indicators: GHG emissions and nitrogen balances.
- Trend analyses showed that more than half of the countries (20 out of 33) registered positive annual growth rates in both WEP and SEP. This group of top growth performers also includes most of the countries that achieved absolute decoupling of their emissions from output growth. These countries can be considered to be on the right trajectory of improving their joint productivity and environmental growth performance (changes in performance over time), albeit with a wide range of growth rates among these countries.
- While there is compelling evidence that TFP growth has helped countries to expand agricultural output and reduce GHG emissions per unit of output, emissions have increased in absolute terms for about half of the OECD countries assessed and N balances for about one-third in the 2006-2015 period. While, in the absence of productivity growth, the absolute growth in GHG emissions and N balances would have been higher, the findings in the report nevertheless suggest that there is room to enhance and steer R&D investments and innovation in the sector in a more environmentally sustainable direction.

Executive Summary

The agricultural sector faces the "triple challenge" of providing enough nutritious food to feed a growing population, supporting the livelihoods of people working in the sector and ensuring its activities are environmentally sustainable. To address this challenge, agricultural productivity needs to improve without compromising natural capital and the state of the environment.

Total factor productivity (TFP) growth in agriculture has the potential to reduce the negative environmental externalities produced by farming activities by reducing the amount of inputs needed to produce a given level of output. However, standard measures of TFP neglect environmental externalities and the contributions of natural capital to agricultural output. Therefore, it is not clear whether standard TFP growth always improves environmental outcomes.

Given these concerns, and the pressing need to better understand the nexus between productivity and the environment, this study explores alternative approaches to provide answers to the following questions:

- Has standard agricultural TFP growth coincided with improved environmental outcomes?
- Has countries' performance with respect to both agricultural productivity and the environment improved over time?

To answer these questions, the study uses two approaches to assess and compare changes in greenhouse gas (GHG) emissions and nitrogen (N) balances[1] and changes in agriculture TFP using the same dataset, which includes TFP growth data published by the USDA ERS, and OECD agri-environmental indicators and covers a sample of 33 OECD countries over 2006-2015.

Overall, the report finds compelling evidence that productivity growth has helped countries to expand agricultural output, while reducing or slowing growth in environmental pressures from the sector. In the absence of productivity growth, the absolute growth in GHG emissions and N balances would have been higher. Nevertheless, GHG emissions increased for about half of the countries assessed and N balances increased for about one third. This suggests that there is room to enhance and steer R&D investments and innovation in the sector in a more sustainable direction.

More specifically, in response to the first question, this analysis shows that improved environmental outcomes have been supported by, or at least coincided with, TFP growth. However, the extent of these improvements has tended to depend on the strength and nature of the TFP growth. This can be seen by examining differences in the TFP growth in two groups of countries that improved their GHG emission intensity of production.

- Countries that achieved an absolute decoupling of agricultural GHG emissions from output growth by simultaneously reducing their emissions and expanding output (39% of the sample) also experienced agricultural TFP growth. This TFP growth was mainly due to savings in inputs, including a reduced reliance on highly-emitting inputs. At the same time, these countries experienced a relative emissions-intensification of their aggregate input bundle, as non-emitting inputs fell faster than emitting inputs.
- Countries that achieved a relative decoupling, where GHG emissions increased, but at slower pace than output (36% of the sample) also registered TFP growth, with the exception of two countries. In the majority of these countries, TFP growth tended to be dominated by an expansion of output growth and was accompanied by an increase in overall inputs, as well as an increase in emitting inputs. Fertiliser use increased in more of these countries than livestock numbers, and fertiliser use accounted for more of their emission increases.

In response to the second question, examples of simple composite indicators, combining changes in a selection of agri-environmental indicators, GHG emissions and N balances with TFP, were used to provide a more complete picture of the combined productivity and environmental growth performance of the sample countries. The weak environment-productivity growth (WEP) indicator involves weighting changes in both

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[1] The analysis addressing question 1 only considers changes in GHG emissions and TFP, while the analysis addressing question 2 considers GHG emissions, N and TFP.

environmental indicators equally and weighting overall environmental growth performance and productivity growth equally. The strong environment-productivity growth (SEP) indicator simply reflects whichever is the worst between the aggregate environmental and TFP growth performance (i.e. weak growth performance in one dimension cannot be offset or substituted by strong growth performance in another).

The analysis based on these two examples of simple composite indicators suggests that most OECD countries have improved their agricultural joint productivity and environmental sustainability growth performance over time, albeit with a wide range of growth rates.

Trend analysis show that 61% of the countries (20 out of 33) registered positive annual growth rates with both SEP and WEP indicators over 2006-2015. On this basis, these countries are on the right trajectory of improving their productivity and environmental growth performance, although growth rates among these countries very considerably. Nine countries achieved positive WEP growth, while suffering a decline in their SEP growth. Four countries registered negative annual growth rates for both composite indicators, suggesting that they have the furthest to go to shift to a trajectory of improved productivity and environmental growth performance.

Under the WEP indicator, all top growth performers increased TFP and reduced their N balances and GHG emissions. For most of the bottom growth performers, TFP growth was low or negative and for most of them, either GHG emissions or nitrogen surpluses or both increased, leading to either a low or negative overall WEP growth performance. The WEP and SEP scores are broadly consistent with the decoupling findings discussed above, in that most of the countries that fall into the absolute decoupling category with regard to their emissions and TFP growth are captured among the top 50% of WEP and SEP growth performers.

1. Introduction

The agricultural sector faces the “triple challenge” of providing enough and nutritious food to a growing population, supporting the livelihoods of people working in the sector and ensuring its activities are environmentally sustainable (OECD, 2021[1]). To address these challenges, the productivity of the agricultural sector has to improve without compromising natural capital and the state of the environment.

Productivity growth in agriculture has the potential to reduce the negative environmental externalities produced by farming activities as it reduces the amount of inputs needed to produce a given level of output. However, standard measures of total factor productivity (TFP) neglect the contribution of natural capital and environmental externalities to agricultural output. Consequently, it is not clear whether or not standard TFP growth is associated with improved environmental outcomes, as shown by the OECD’s Agri-Environmental Indicators (AEIs) (OECD, 2021[2]). In recent decades OECD countries have seen increases in GHG emissions (which can also be viewed as the use of a country’s carbon budget) and biodiversity losses (as measured by farmland birds’ indicators). In highly productive OECD countries (as measured by labour productivity), further improvements in productivity may not necessarily lower GHG emissions intensities if they are reliant on more intensive use of intermediate inputs (OECD, 2019[3]).

Given these concerns, there are several attempts underway to expand the measurement of productivity to include environmental inputs and outputs, including those discussed and reported under the OECD Network on Total Factor Productivity and the Environment,[2] see (OECD, 2022[4]). These approaches either involve including natural capital and pollutants as inputs into the production function or as undesirable outputs, to construct environmentally adjusted measures of TFP. While these approaches are consistent with production economic theory, they are empirically demanding to apply in practice (OECD, 2022[4]). Nevertheless, these advances have helped to generate knowledge about the challenges embedded in this exercise, and about the pros and cons of different approaches. These points are elaborated further in Section 2. There are also efforts to measure productivity and environmental sustainability at farm level such as those under the OECD’s Farm Level Analysis Network (Sauer et al., 2021[5]; Sauer and Moreddu, 2020[6]). Those results are rarely representative of country-level performance but provide useful granular information of specific production systems.

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[2] See https://www.oecd.org/agriculture/topics/network-agricultural-productivity-and-environment/.

Given the various concerns above about standard measures of TFP neglecting the contributions of natural capital, and the pressing need to better understand the nexus between productivity and the environment this study explores alternative approaches to provide answers to the following research questions:

- Has TFP growth coincided with improved environmental outcomes?
- Has countries' performance with respect to both productivity and the environment improved over time?

To answer the first question, a simple approach involving the decomposition of changes in environmental outcomes into components associated with TFP growth, output and input use, is developed. To answer the second question, a composite indicator approach is developed to measure countries' productivity and environmental sustainability growth performance, which makes use of the best information that is available in a pragmatic manner. These include the USDA's International Agricultural Productivity database and the OECD's Agri-Environmental Indicators.

Combining the data from the standard TFP with a set of OECD Agri-Environmental Indicators (AEIs) that are most policy relevant provides a pragmatic way forward in assessing combined performance on productivity growth and the environment growth performance, since these data are already available. This approach can shed light on the potential synergies and trade-offs between these two important policy objectives. Moreover, the composite indicators that jointly evaluate productivity growth and environmental growth performance show potential for country benchmarking and policy analysis, as trends in composite indicators are easier to report than a battery of many single indicators.

The composite indicator approach to TFP and environmental performance (TFPE) has much in common with some types of environmentally-adjusted TFP (EATFP) measurement.[3] That said, one of the main differences is that the present composite indicator approach uses a simple weighting scheme and avoids the substantial challenges EATFP measurement faces in deriving weights for combining production variables and environmental variables based on economic considerations (e.g. weights that are consistent with profit maximisation and externality pricing). This provides a complement and alternative to EATFP measurement, that may offer a simple construction method and indicator that is more straightforward to calculate.

The measurement of agricultural productivity at country level is typically done through estimates of the TFP of the sector. The most well-known research effort in this area is the "International Agricultural Productivity" data product, which uses a growth accounting methodology to measure annual TFP growth for countries (ERS-USDA, 2023[7]). This provides a standardised methodology for international comparisons in TFP growth, but not levels. The ERS-USDA (2023[7]) provide the best available global database for making international comparisons, due to the large number of countries included and the consistency of data sources and methods used to create TFP indexes.

However, there are other TFP databases and studies that focus on individual countries or groups of countries, which use different data and methods and can therefore provide different TFP results and insights. This includes the "Agricultural productivity in the US" data product (ERS-USDA, 2023[8]), which uses more detailed domestic data. For European Union countries, other studies are available, such as the European Commission (2016[9]), which also takes advantage of more detailed country-level data than that used in the global ERS-USDA (2023[7]).

The OECD has already combined the two global sets of indicators (ERS-USDA (2023[7]) and the agri-environmental indicators (OECD, 2021[2]) to assess the environmental sustainability and productivity performance of countries (OECD, 2021[10]; OECD, 2021[11]). The OECD has also used similar composite indicators of productivity and sustainability to analyse the impacts of agricultural policies on country performance (OECD, 2019[12]; Lankoski and Thiem, 2020[13]) using different degrees to which increases in productivity can substitute declines in environmental sustainability and natural capital following the concepts of strong and weak sustainability (Ekins et al., 2003[14]). This paper systematically explores available options and necessary methodological aspects for constructing composite indicators and their potential for country benchmarking and policy impact analysis. It builds on the previous OECD work and on the OECD guidelines for constructing composite indicators (OECD/European Union/EC-JRC, 2008[15]).

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[3] See Section 2.3 for more explanations on this comparison.

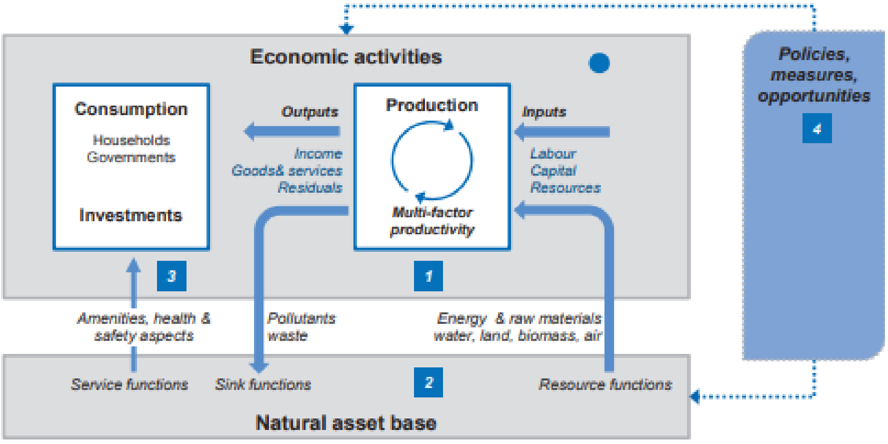
This paper is structured as follows. Section 2 presents an analytical framework to guide the empirical analyses in the report. Section 3 provides an overview of the data and describes the selection of indicators used in the analyses. In Section 4, results decomposing GHG emission changes into contributions from TFP, input and output changes, are presented to shed light on research question 1. Following this, results based on two examples of simple composite indicators of productivity growth and the environment are also presented in Section 4, to provide answers to research question 2. Finally, Section 5 summarises the main lessons learned from analysis, including the discussion of results and potential next steps.

2. Analytical framework

2.1. The OECD sustainable productivity framework and challenges

OECD has developed a sustainable productivity framework to be used as a tool to assess policy performance with respect to the long-term productivity and environmental sustainability performance of countries (OECD, 2020[16]). In this framework agricultural production relies on fundamental biological processes, which combine various natural resources, the stock of which is an asset or “Natural Capital”, with other inputs (Figure 2.1). In the Framework, sustainable productivity refers to productivity growth compatible with the preservation of natural capital in the short and long run. Like physical capital, natural capital needs investment and maintenance to retain its productive capacity in the long run. To be sustainable, productivity growth will also need to be resilient to climate change and account for greenhouse gas emissions and other environmental impacts that flow from production.

Figure 2.1. OECD Framework for productivity and sustainability



Note: Multifactor Productivity (MFP).
Source: Adapted from The OECD Green Growth Measurement Framework (OECD, 2014[18]).

The OECD framework takes a holistic view of “productivity”, which is defined as TFP, a concept which considers the efficiency with which firms combine all inputs to produce outputs. Conceptually, this notion of productivity has been extended to include natural resources and environmental goods and services. Therefore, progress towards sustainable productivity could be measured by considering holistic TFP measures, such as environmentally adjusted TFP that include the use of natural resources.

As outlined in OECD (2022[17]), standard TFP growth measures cannot separate technical change from an increase in the use of natural capital or pollutant by-products unless they are corrected for these. Approaches for constructing environmentally adjusted TFP indices involve the inclusion of these environmental externalities as either inputs or undesirable outputs that are “weakly disposable” (that is, they are costly to reduce and require the use of resources that would otherwise be used to produce agricultural commodities). These approaches are consistent with production economics theory, but they face a number of empirical challenges. Foremost among these, is the selection and construction of appropriate weights for environmental externalities, which allows for their consistent aggregation with the standard production inputs and outputs. This challenge stems from the fact that these externalities do not have market prices, which are the basis for creating weights for standard production variables. There are solutions, which typically require the computation of the shadow prices of environmental externality variables. Despite advances, the establishment of a practicable approach for measuring environmentally-adjusted TFP, that is sufficiently simple for the routine calculation by statistical agencies, remains elusive (OECD, 2022[4]).

2.2. Decomposing changes in environmental flows in reference to TFP

2.2.1. Standard growth accounting measure of TFP

In this section, a simple decomposition approach is outlined to bring TFP and GHG emissions into the same mathematical expression, to be able to relate changes in GHG emissions to changes in TFP and other relevant variables.

First, it is necessary to define the relevant variables and the standard growth accounting approach for calculating TFP. Total factor productivity (TFP) is defined as the ratio of total output, *Y*, to total inputs, *X*. Thus, TFP is simply:

$$TFP = Y/X \qquad (1)$$

Changes in TFP over time are found by comparing the rate of change in total output with the rate of change in total input. Expressed as logarithms, changes in equation (1) over time can be written as

$$\frac{d\ln(TFP)}{dt} = \frac{d\ln(Y)}{dt} - \frac{d\ln(X)}{dt} \qquad (2)$$

Considering that agriculture produces multiple outputs, using multiple inputs, *Y* and *X* are vectors of these variables. Assuming that markets are in competitive equilibrium and the underlying technology is represented by a constant-returns-to-scale production function, then the output elasticity with respect to an input is equal to the cost share of that input. With these assumptions in place, equation (2) can be written as:

$$ln\left(\frac{TFP_t}{TFP_{t-1}}\right) = \sum_i R_i\, ln\left(\frac{Y_{it}}{Y_{it-1}}\right) - \sum_j S_j\, ln\left(\frac{X_{jt}}{X_{jt-1}}\right) \qquad (3)$$

where S_j is the cost-share of the j-th input and R_i is the revenue share of the i-th output. Using the function g(.) to signify the annual rate of growth in a variable, and considering output in aggregate, this presentation of the expression can be simplified to:

$$g(TFP) = g(Y) - \sum_{j=1}^{j} S_j g(X_j) \qquad (4)$$

2.2.2. Relating GHG emissions to TFP

To bring TFP and GHG emissions into the same expression, GHG emissions are first defined as *E*, and then expressed as the product of the emission intensity of production (E/Y) and output *(Y)* yields the following expression: $E = \frac{E}{Y}Y$. Then dividing the numerator and the denominator of the emission intensity term in this expression by *X,* gives: $E = \frac{E/X}{Y/X}Y$. The denominator of this expression is the TFP measure, and if the numerator (E/X) is defined as the emission factor (EF) of input use. The expression can be rewritten more compactly as: $E = \mathrm{Y}\frac{EF}{TFP}$. This equation can be expressed as in annual change form as:

$$g(E) = g(Y) - g(TFP) + g(EF) \qquad (5)$$

This equation is framed from the perspective that GHG emissions are tied to emitting production inputs. It simply reveals that for TFP growth to be mitigating the following condition must hold: $g(TFP) > g(Y) + g(EF)$. A further requirement assumed here for decoupling is that output growth also needs to be positive, i.e. $g(Y) > 0$. And if output growth is positive, and the emission factor of input use remains unchanged (assuming for instance that input use and emissions have a fixed relationship and move in lockstep) then the growth in TFP would need to exceed the growth in output, i.e. $g(TFP) > g(Y)$, for TFP growth to be compatible with an absolute decoupling of emissions. Since $g(TFP)$ is simply equal to $g(Y) - g(X)$, $g(TFP)$ can only exceed $g(Y)$ if $g(X) < 0$. However this will not be sufficient if, in the process, the input bundle becomes too emission intensive (i.e. in situations where $g(EF) > g(Y) - g(TFP)$) which could happen if the TFP growth is reliant on an increase in emitting inputs, despite an overall reduction in input use.

Furthermore, TFP growth that is not input-saving could be compatible with an increase in overall input use, i.e. when $g(TFP) < g(Y)$ and where $g(X) > 0$, providing there is an offsetting decline in *EF*, which could occur if the aggregate input bundle is sufficiently de-intensified. This could, for instance, happen if there is an increase in input resources devoted to abating emissions.

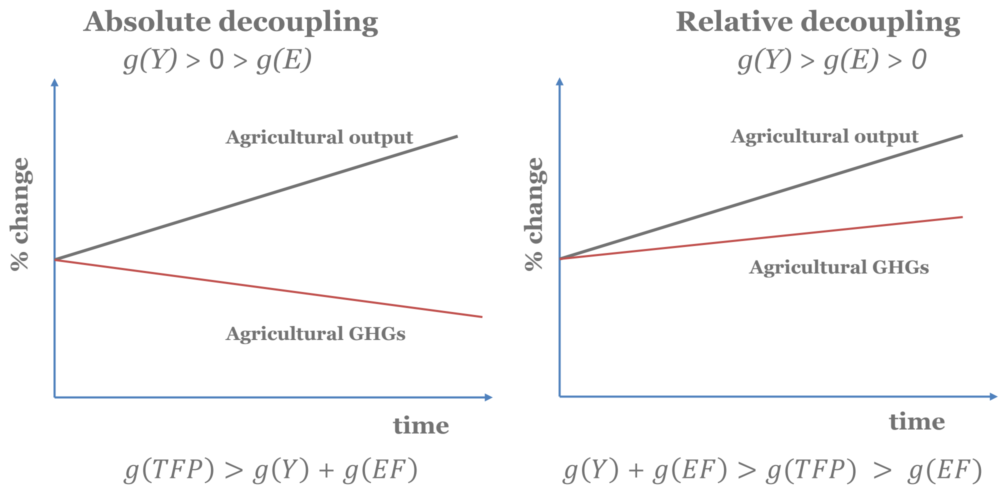
2.2.3. Emission intensities and decoupling in the context of TFP

The concept of emissions decoupling directly relates to the emission intensity of output, which can be defined as $EI = E/Y$. This can be achieved with both an absolute and relative decoupling of emissions from output growth. In both cases, output growth needs to be positive, $g(Y) > 0$, and it needs to grow faster than emissions, i.e. $g(Y) > g(E)$. For absolute decoupling, the following needs to hold: $g(Y) > 0 > g(E)$.

These decoupling concepts can also be framed with respect to the emissions decomposition presented in the previous section, in order relate back to TFP growth. As outlined in the previous section, when output growth is positive absolute decoupling requires that $g(TFP) > g(EF) + g(Y)$, while relative decoupling occurs when $g(EF) + g(Y) > g(TFP) > g(EF)$.

These decoupling concepts are presented in Figure 2.2 below, along with the correspondence between their definitions in terms of a) output and emissions changes (at the top of the figure), and b) the output, TFP and EF changes (at the bottom of the figure).

Figure 2.2. Concepts of absolute and relative decoupling



2.2.4. Further decomposition of emission changes into their underlying components

As outlined in Section 2.2.2, in equation (5), repeated here below for ease of reference, provides a simple lens for understanding how the type of TFP growth matters when it comes to GHG mitigation.

$$g(E) = g(Y) - g(TFP) + g(EF)$$

However, the *EF* variable above aggregates a large amount of information, while growth in this variable can signify a deterioration in environmental performance, its growth can also be compatible with emission reductions. This is because the variable imply reflects a relative change in emissions per overall input use, which means it can increase when emissions decline simply because other inputs decline faster. Therefore, further decomposition of this variable is needed to render it useful for interpretation by environmental policy makers.

To do this it helps to distinguish emitting inputs from non-emitting inputs. The change in the total input bundle has already been defined as:

$$g(X) = \sum_{j=1}^{j} S_j \, g(X_j)$$

The vector of inputs can then be separated into two mutually exclusive subsets, X_E and X_{-E}, i.e. $X = (X_E, X_{-E})$. Let $k = 1, \dots, K$, where $k \leq j$, be the index for the vector of emitting inputs X_E. The change in aggregate emissions can then be defined as:

$$g(E) = \sum_{k=1}^{k} \gamma_k \, g(E_k)$$

Where $g(E)$ is now defined as the change in the bundle of emitting inputs, in which the change in each of the k-th emission weighted by its share (in physical terms) of the total emissions bundle, γ_k. Using this notation, and defining the emission factor of each emitting input as $EF_k = \frac{E_k}{X_k}$, the change in aggregate emissions can be decomposed into the contributions from each emitting input and their emissions using the following equation:

$$g(E) = \sum_{k=1}^{k} \gamma_k \left(g(EF_k) + g(X_k)\right) \tag{6}$$

And the aggregate emission factor can be decomposed as follows:

$$g(EF) = \sum_{k=1}^{k} \gamma_k \left(g(EF_k) + g(X_k)\right) - g(X) \tag{7}$$

These simple decompositions of the changes in aggregate emissions and the aggregate EF, provide clarity with respect to their underlying drivers. They show the extent to which mitigation and the relative intensification of the input bundle are compatible, and enable emission changes to be linked to the level of use of each emitting inputs (X_k) which include animals, fertiliser and irrigated rice paddies, their individual emission factors (EF_k), and change in total input use (*X*).

2.3. Combining TFP and AEIs in a simple composite indicator of productivity and environmental growth performance

Based on (Cárdenas, and Souchier, 2018[19]) an environmentally-adjusted TFP measure (*EATFP*), which considers the incorporation of natural capital and environmental externalities (Z) as inputs into a sector's production function could be measured as:

$$g(EATFP) = g(Y) - \sum_{j=1}^{j} \varepsilon_j g(X_j) - \sum_{k=1}^{k} \varepsilon_k g(Z_k) \tag{8}$$

Equation (8) essentially expands the standard growth accounting formula in equation (4) to include non-only market inputs (*X_j*) but also natural capital and environmental externalities (*Z_k*). Recall that, for the standard TFP measure described in equation (4), the cost shares of the inputs reflect the elasticity of input use per unit of output, under the assumptions of competitive markets, profit maximisation and constant returns to scale. Equation (8) is a more general representation, using elasticities ε instead of cost shares.

Given the challenges in creating and the absence of a practicable method for calculating this EATFP, this study explores alternative approaches for using existing TFP and AEI data to evaluate whether countries' performance with respect to productivity and sustainability has improved over time. The approach proposed to address the question considers combining the standard measures of TFP, calculated by the USDA (2022), using the growth accounting method outlined in Section 2.2.1, with a set of policy-relevant OECD Agri-Environmental Indicators that are suitable for national scale analysis.

Before delving into this, it is helpful to take another look at the measures of TFP growth calculated by the USDA and outlining, at a very general level, what a simple approach to adjusting this measure to account for environmental externalities might look like. This provides a useful theoretical vantage point from which to view proposed alternatives. Recall that TFP is defined as the ratio of total output to total inputs, and was expressed in annual growth terms in equation (4), repeat here again for ease of reference:

$$g(TFP) = g(Y) - \sum_{j=1}^{j} S_{Xj}\, g(X_j)$$

If environmental variables are considered as input variables, defined here as Z and distinguished from standard input variables, X. An environmental input variable could, for instance, be GHG emissions and to give it a clearer orientation as an input, it could be thought of as a carbon-budget that gets used to produce output. Assuming further that the weight for the environment input variable (φ_k) is known (based for instance on an appropriate shadow price or cost shares) then the above expression could be expanded to a version of TFP growth accounting measurement that accounts for environmental impacts or natural capital variables Z that we define as TFPE (Total Factor Productivity Growth and the environment) to differentiate it from the EATFP:

$$g(TFPE) = g(Y) - \sum_{j=1}^{j} S_j\, g(X_j) - \sum_{k=1}^{k} \varphi_k\, g(Z_k) \qquad (9)$$

Subject to, $\sum_{j=1}^{j} S_j \mp \sum_{k=1}^{k} \varphi_k = 1$

This formulation shows that a positive change in either the environmental variable or standard input variable will have a share-weighted negative impact on TFPE. This is one possible formulation for TFPE which, as mentioned, can provide a useful reference point from which to compare proposed alternatives, in terms of what they measure instead. It is worth emphasising here that there are significant challenges in constructing appropriate cost shares for the environmental variables.

One alternative approach developed by (Lankoski and Thiem, 2020[13]) and employed, for example, in the 2021 *OECD Norway Review* (OECD, 2021[11]), aggregates the standard TFP measures with AEI indicators based on the substitutability between economic and environmental performance. This aggregation approach is based on the concepts of a strong and a weak sustainability. Weak sustainability postulates the full substitutability of natural capital whereas the strong conception demonstrates that this substitutability should be limited due to the existence of critical elements that natural capital provides for human existence and well-being, see e.g. (Ekins et al., 2003[14]).

Based on the notions of weak and strong sustainability, two alternative sustainable productivity concepts have been developed following (Lankoski and Thiem, 2020[13]):

- *Weak environment-productivity growth (WEP)*: a weak sustainability rule is adopted which allows full substitution between different environmental outcomes and between productivity and environmental sustainability outcomes. (Lankoski and Thiem, 2020[13]).
- *Strong environment-productivity growth (SEP)*: a strong sustainability rule is adopted, which means that low performance in one of the environmental sustainability dimensions cannot be substituted with high performance in other environmental sustainability dimensions. Similarly, SEP does not allow substitution between environmental sustainability and productivity outcomes.

For the purpose of exposition, the weak sustainability aggregation method is considered here in reference to the equations above. The weak sustainability rule simply allows substitution between productivity and environmental indicators, under the assumption of equal weighting between annual changes in TFP and a selection of environmental performance variables. Defining the environmental indicator as Z, this WEP composite indicator can be defined as:

$$g(WEP) = average(g(TFP) - g(Z)) \tag{10}$$

Taking the average of these two terms on the right side of the equation is the same as assuming that they have equal weights. Breaking this equation down further into its component parts, allows more direct comparison with equation 5 above:

$$g(WEP) = 0.5\big(\mathrm{g}(Y) - \mathrm{g}(\mathrm{X}) - g(Z)\big) \tag{11}$$

Comparing this to equation (9) above reveals some similarities and some differences with the TFPE indicator. Equations (9) and (11) will only be equal when a) output is constant, and b) if the shares between the standard input variables and the environmental variables in equation (9) are equal. If b) holds, but a) does not and there is a change in output, the two scores will differ by $0.5g(Y)$. If neither a) nor b) hold, then the two expressions will differ by $0.5g(Y)$ and by $\sum_{j=1}^{j}\Big((0.5 - S_j)g(X_j) + (0.5 - \varphi_k g(Z_k)\Big)$.

If the WEP indicator is created by instead combining the standard TFP measure with an environmental indicator of its intensity per unit of output E/Y, so that WEP is defined as $g(WEP) = average\left(g(TFP) - g\left(\frac{Z}{Y}\right)\right)$, it can also be expressed as: [4]

$$g(WEP) = 0.5(2g(Y) - g(X) - g(Z)) = g(Y) - 0.5g(X) - 0.5g(Z) \tag{12}$$

Equation (12) shows that WEP is calculated with the same formula as for TFPE in equation (9) but imposing elasticities (degrees of substitution) of 0.5 to both market inputs X and environment outcomes Z. The difference between this emission intensity version of the WEP indicator and the TFPE measure, shown in (9) will be equal to $\sum_{j=1}^{j}\Big((0.5 - S_j)g(X_j) + (0.5 - \varphi_k)g(Z_k)\Big)$.

Therefore, defining WEP as the combination of TFP and E/Y brings the WEP and TFPE expressions closer together, by eliminating one source of divergence, namely $0.5g(Y)$. Moreover, this formulation shown in equation (12) is the same as a special case of the TFPE index in which the weights between the composite of standard and environmental inputs are equal (i.e. in where $\sum_j S_j - \sum_k \varphi_k = 0$). Nevertheless, these weights are unlikely to be equal and constant over time, therefore WEP equation (8) would only provide a rough approximation to a TFPE function in which the weights are known.

Still, the WEP-based composite indicator is a pragmatic approach that could provide useful insights about the productivity and environmental performance trajectory of countries. This stream of work will also help to generate deeper discussions about the sustainability performance of countries and shed more light on synergies and trade-offs between productivity and environmental sustainability policy objectives.

Alternative approaches for generating weights are also proposed in literature. This includes the aforementioned strong sustainability concept for aggregation of TFP and environmental variables, which is based on the notion that various environmental sustainability outcomes and economic performance are not substitutable. With this approach a weight of 100% is given to the weakest performing indicator, that is the indicator with the lowest growth rate (the lowest negative growth rate in the case of the environmental sustainability variables). Any country that performs well under such a strict weighting criterion can be considered to be on a solid trajectory for improving the productivity and environmental performance of their agriculture sector.

Given the importance of weights and their impact on the composite indicators, efforts are made to unpack, in detail, the results obtained using these indicators in Section 4.2.2.

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[4] This can be shown by first considering the elementary (or undifferentiated) equation from which this expression is derived: $WSP = 0.5\left(\frac{Y}{X}/\frac{Z}{Y}\right)$, which can also be expressed as $WSP = 0.5\left(\frac{Y^2}{XZ}\right)$.

3. Data overview and selection of indicators

Different indicators can be used to track both productivity and the environmental performance of agriculture. At the country level, the United States Department of Agriculture (USDA) calculates and publishes Total Factor Productivity indicators for 187 countries (USDA Economic Research Service, 2021[20]). This TFP measure is a ratio of outputs to inputs. This ratio is calculated using the growth accounting method, and thus measures the productivity changes in a country over time, using an accounting method that is consistent across countries. When output grows at a higher rate than inputs grow, TFP increases and when output increases at a lower rate than inputs, TFP declines (USDA Economic Research Service, 2021[20]). This allows the comparison of country growth rates in TFP over time, but does not provide information on the TFP levels.

By contrast, multi-country indicators of the environmental sustainability performance of agriculture are produced by OECD (OECD, 2021[21]), EUROSTAT (EUROSTAT, 2021[22]) and FAO (FAOSTAT, 2021[23]). The OECD tracks more than 50 indicators covering all 38 OECD countries and 17 countries not members of the OECD over the period 1990-2018. These indicators focus on specific aspects of the environmental performance rather than providing an overall assessment. The double challenge is to identify the right set of indicators that capture the overall agri-environmental performance, and to identify the way to bundle them to estimate a composite productivity–environmental sustainability indicator.

Composite indicators of productivity and environmental sustainability are not available at the country level. To guide the discussion in terms of the potential indicators that could be used for joint assessment of productivity and environmental sustainability, this section of the report reviews insights from the literature, presents the coverage of the OECD agri-environmental indicators and their use to measure agri-environmental performance.

3.1. AEIs used in the literature for sustainability assessments

One of the difficulties in finding suitable indicators for measuring environmental sustainability in agricultural systems stems from the multiple definitions of environmentally sustainable agriculture that are available. The definition used here is the one of the OECD Productivity-Sustainability-Resilience Framework, for which sustainability “refers to the preservation of natural capital, i.e. environmental sustainability. This encompasses managing agriculture’s use of natural resources to ensure their long-term viability and reducing the negative environmental impacts of agriculture production which can damage the natural assets” (OECD, 2020[16]). This definition encompasses only the environmental dimension of sustainable development, which was defined by the World Commission on Environment and Development in 1987 as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

A review of 34 studies on the sustainability performance of agriculture reveals that some of the environmental domains most commonly covered in sustainability assessments of agriculture are water (e.g. water use, water availability, water footprint, water use intensity), nutrients (e.g. nutrient balances, fertiliser application), agricultural area, land use and land use change (e.g. agricultural area by type, deforestation rates, agricultural land use change), soil indicators (e.g. soil erosion, soil organic content, soil characteristics) and air emissions (e.g. GHG and ammonia) (Table 3.1). The literature review consisted of a web search in Mendeley using the keywords sustainability, environmental indicators and agriculture which yielded more than 100 articles. Further screening of those articles to consider only those that include indicators with measurement units using country or region aggregates yielded 34 relevant studies on the sustainability performance of agriculture. Those studies include 257 agri-environmental indicators that were organised in 10 environmental domains. This report focuses on those agri-environmental indicators that are more closely related to the definition of sustainable agriculture of the OECD (OECD, 2020[16]).

Studies focusing on the sustainability of agriculture tend to be comprehensive in terms of the environmental domains explored and on the number of indicators included. On average, each study included five environmental domains and two indicators per domain (Table 3.2).

Overall, these results suggest that environmental sustainability involves multiple environmental domains and that no single indicator may represent a single domain.

Table 3.1. Indicators domain in sustainability of agriculture studies

Domain	Number of indicators
Water	41
Nutrients	38
Agricultural area, land use and land use change	36
Soil	33
Air emissions (GHG and Ammonia)	28
Biodiversity, habitat and landscape	25
Energy	21
Pesticides	13
Sustainable practices	11
Livestock	11

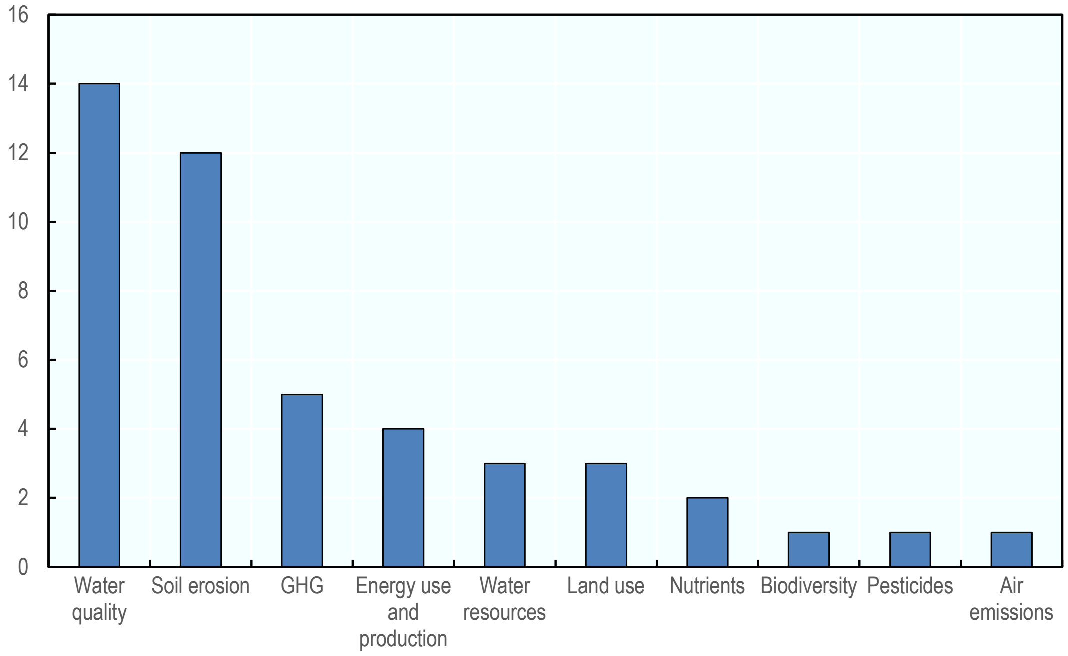
Table 3.2. Summary statistics of domains and indicators per study

	Mean	Standard deviation	Min	Max
Domains/study	5.4	2.4	1	9
Indicators/domain/study	2.1	1.8	1	13

3.2. Scoping the use of OECD agri-environmental indicators

The OECD AEIs include more than 50 indicators grouped into ten environmental domains (Figure 3.1).

Figure 3.1. Number of AEIs by agri-environmental domain



Source: OECD (2021[21]).

Previous work conducted by the OECD identified a set of key agri-environmental indicators to track the environmental performance of agriculture (OECD, 2022[24]). These indicators are published in the *Measuring the Environmental Performance of Agriculture Across OECD Countries* web publication in the form of a dashboard showing trends and levels of those indicators for each OECD country. The portrayed agri-environmental indicators in the OECD dashboard are the following:

a) Agricultural land use change

b) Nitrogen and phosphorus fertiliser use per area of agricultural land

c) Water abstraction per area of agricultural land

d) Direct on-farm energy consumption per area of agricultural land

e) Nitrogen and phosphorus balances (nutrient surplus/ha)

f) Nitrogen and phosphorus use efficiency (nutrient outputs/nutrient inputs)

g) Agricultural GHG emissions

h) Agricultural GHG emission intensity (Agricultural GHG emissions/Value of output)

i) Agricultural ammonia emissions

j) Farmland birds index

Those indicators were selected on the basis of data availability, environmental and policy relevance.[5] While the agri-environmental indicators of the dashboard give a broad perspective of the main environmental pressures associated with agricultural activities, they warrant additional scrutiny to be used in joint productivity and sustainability assessments and country benchmarking. First, some indicators such as farmland birds and ammonia emissions are unavailable for a broad set of countries; some other indicators such as water abstraction have few observations per country over time. Second, and more importantly, there are differences between the responsiveness of specific indicators to policies. For example, the effects of support policies on water abstraction rates are not likely to be immediate because those indicators depend heavily on structural conditions such as irrigation equipment and investment, water allocation regimes and available water sources (surface or groundwater). In contrast, support policies can have a more direct and immediate impact on indicators that are more directly linked to changes in production intensity, such as GHG emissions or nutrient balances.

OECD AEIs that have a comprehensive coverage of time periods and countries include direct on-farm energy consumption, GHG emissions, nutrient balances and area under organic production (Table 3.3). Other relevant indicators, including ammonia emissions, pesticide sales, water abstraction, farmland bird indicators, irrigable area and area eroded by water, have a lower country and time coverage. Those indicators that are available for a large number of countries and periods represent four environmental domains according to the classification in Table 3.1: energy, nutrients, air emissions and agricultural area, land use and land use change. Two important dimensions often portrayed in sustainability assessments do not have good country-time coverage in the OECD AEIs: water and soil.

Moreover, not all of the indicators with good coverage have a meaningful link with the environmental performance of agriculture. While greenhouse gas emissions have a direct link with global warming and nutrient balances are related to water and air pollution due to higher risk of nutrient runoff and emissions to air (OECD, 2019[3]), the linkage between the environmental pressures associated with organic area and energy consumption are less direct (OECD, 2008[25]). Organic farming decreases the use of pesticides and inorganic fertilisers which can favour biodiversity, improve soils and water quality but does not necessarily reduce greenhouse gas emissions (OECD, 2016[26]). It can also induce higher use of inputs in non-organic areas due to lower yields associated with the adoption of organic agriculture practices (Tuck et al., 2014[27]; Gabriel et al., 2013[28]). Direct on-farm energy consumption can generate air pollution

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[5] The dashboard also includes agriculture characteristics indicators such as the extent of agricultural land area by type (total, cropland and pasture), the number of livestock units, the share of livestock production in the total value of agricultural production and the share of irrigated area in total agricultural area.

associated with the use of fossil fuels to operate machinery and greenhouses, but that association is weak in areas where the energy matrix is composed by renewable and clean energy sources.

Given the above discussion on coverage of time periods and countries of OECD AEIs as well as policy relevance and suitability of the indicators for country level analysis ensuing data analysis focuses on GHG emissions and nitrogen balances. These selected AEIs reflect well environmental pressures on climate change, air quality and water quality and they are well-suited to country scale analysis. For these selected AEIs a complete coverage of 33 countries and 16 time periods (years 2000-2015) will be employed in following analysis.

The first step for combining different variables into a composite index (in this case, productivity and environmental variables) is to ensure that they are logically compatible. For this to hold, all of the variables need to either be in annual change form or in levels. Since there has not been full agreement on how to compare different levels of environmental indicators across countries and since the TFP index used in this study is only available in annual change format, the environmental variables combined with this index should also be in annual change format. To provide the clarity on terms used in this study the terms "environmental growth performance" and "growth performance" are introduced in reference to the annual changes of the respective environmental performance indicators.

Table 3.3. Summary statistics of selected OECD AEIs

Indicator (units)	Average value	Max	Min	Average number of periods	Number of countries in database with at least one observation	Number of OECD countries in database
Energy consumption (1000 toe)	3 247	42 849.8	0.0	19	55	38
GHG emissions (1000 t CO_2e)	75 434	691 256.1	64.8	19	55	38
Nitrogen balance (Tonnes)	2 006 896	32 300 000.0	-3 218 487.0	18	53	36
Nitrogen balance per ha (kg/ha)	63	320.0	-14.8	18	53	36
Phosphorus balance (Tonnes)	335 469	6 751 204.0	-592 339.9	18	53	36
Phosphorus balance per ha (kg/ha)	8	72.0	-9.0	18	53	36
Area under organic production (ha)	751 538	27 100 000.0	1.0	15	55	38
Ammonia emissions (1000 t)	257 998	3 945 000.0	1 226.7	14	41	33
Pesticide sales (Tonnes)	65 988	1 815 690.0	2.3	10	52	38
Water abstraction (1000 m3)	13 409	192 485.3	0.1	9	38	36
Farmland birds index (2000=100)	91	130.1	30.3	8	28	27
Irrigable area (ha)	1 762 662	25 400 000.0	0.0	6	37	37
Area eroded by water (ha)	1 033	16 583.5	0.0	2	29	23

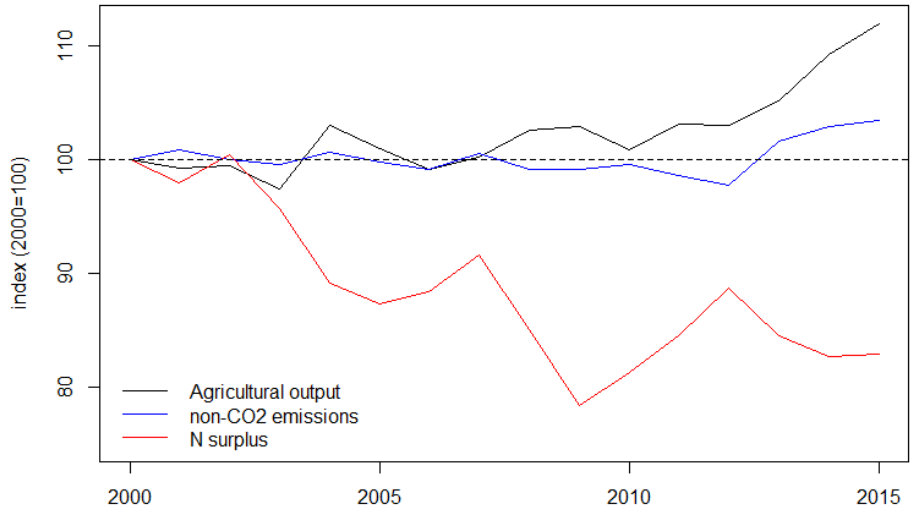
Note: Period 1997-2016.
Source: OECD (2021[21]).

4. Results and discussion of the analysis of joint productivity and environmental performance analysis

4.1. Has TFP growth coincided with improved environmental outcomes?

Before addressing this question, it is worth first taking a look at how growth in agricultural production and a selection of its environmental impacts have evolved over time, to see if there is evidence of an aggregate decoupling of these impacts from production, for the 33 countries in the study sample. As shown in Figure 4.1, there has been some decoupling of non-CO_2 emissions from the growth in agricultural output and a complete decoupling of this growth from N surpluses, at an aggregate level. This stronger environmental growth performance in relation to N surpluses may be due to more effective policy incentives and regulations controlling N pollution than for GHG emissions from agriculture, although this requires further investigation.

Figure 4.1. Agricultural output, non-CO_2 emissions and N surplus trends

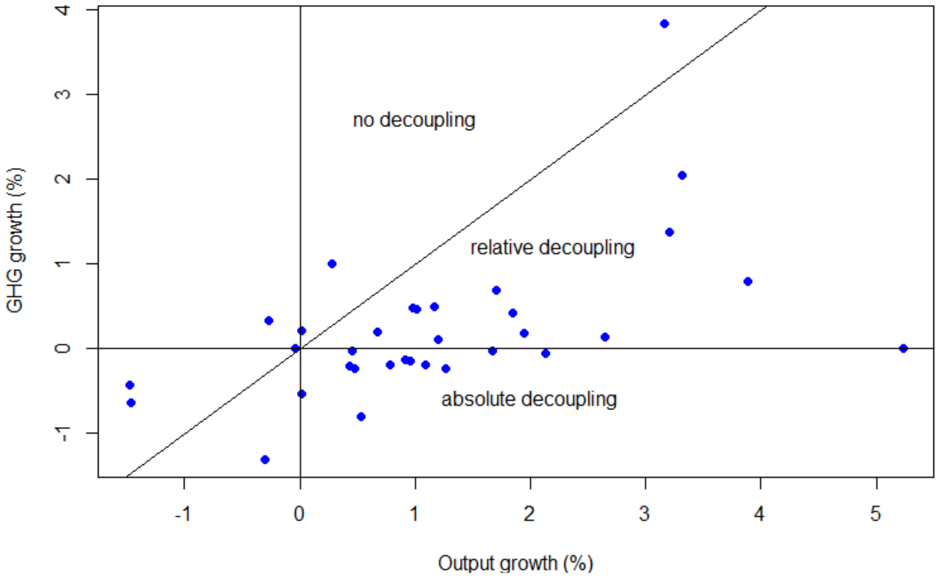


Note: Constant 2004-2006 global, purchasing-power-parity, average farm prices, are used to represent agricultural output in terms of approximate volume changes, while the non-CO_2 agricultural emissions are summed over different sources and gases based on their global warming potentials.

Underlying this aggregate picture are country-level trends which display a mix of absolute and relative decoupling and, in a few cases, increases in the degree to which environmental impacts are coupled with production. These country level results are shown for GHG emissions and production for each sample country, in the quadrant chart shown in Figure 4.2.

For 36% of countries, emissions have increased, but at a slower pace than output, allowing them to achieve a relative decoupling of emissions from output growth (Figure 4.2). These countries are shown below the 45 degree line in the top right-hand quadrant of the chart. A further 39% of countries (shown in the bottom right-hand quadrant) have achieved absolute decoupling, by growing their agricultural output while simultaneously reducing emissions.

Figure 4.2. Annual growth in production and emissions (2006-2015)



Further insights about the components underlying the decoupling relationships can be gained by viewing the changes in emissions through the decomposition lens described in Section 2.2.[6] This decomposition is shown for all of the countries in the sample that experienced either an absolute decoupling (Figure 4.3a) or relative decoupling (Figure 4.3b) of the emissions from output. Significantly, all of the countries that achieved an absolute decoupling, also experienced a growth in their agricultural TFP. While all except two countries that relatively decoupled their emissions from output, registered TFP growth.

For all countries that achieved absolute decoupling (Figure 4.3a), TFP growth has helped to expand output, and it has also tended to increase the EF of input use, but not by enough for GHG emissions to rise. As shown in Figure 4.3b, the relative decoupling only depended on TFP growth being higher than growth in the EF of inputs. Meeting this condition was sufficient to keep emissions per unit of output from rising for these countries.

The reasons for this tendency of TFP growth to be accompanied with a growth in EF, in and of itself is not a problem, especially for the countries that achieved an absolute decoupling of emissions, since their improvements in production and GHG mitigation outcomes are unambiguous. The aggregate EF combines multiple factors and cannot be usefully interpreted without further unpacking. For instance, it can rise simply due to a faster reduction in non-emitting inputs than in the reduction of emitting inputs. This would increase the share of emitting inputs used within the input bundle, but would still represent an improved environmental outcome. Thus, TFP growth that coincides with a relative intensification of the input bundle is certainly compatible with GHG mitigation. In other cases, an increase or a decrease in the relative intensification of the input bundle is associated with higher emissions (as is the case for all countries that only achieve relative decoupling). Further unpacking of the sources of emission and EF changes is needed to determine their underlying causes, as done below in Figure 4.4.

For each country, the contributions of fertiliser use, livestock and rice (in the case of Japan, Korea) are presented in Figure 4.4. The shaded orange bars show changes in the amounts of these inputs, and the solid orange bars show changes in the emission factor specific to these inputs. Adding these two orange bars together gives their contribution to the total emission changes for agriculture, marked as a diamond, for each country and emitting input. The sum of the changes represented by diamonds, across inputs within each country, is equal to the emission changes in Figure 4.3. Adding the reduction in aggregate input use (the blue shaded bar) to the changes in each emitting input and its specific EF reveals, the relative

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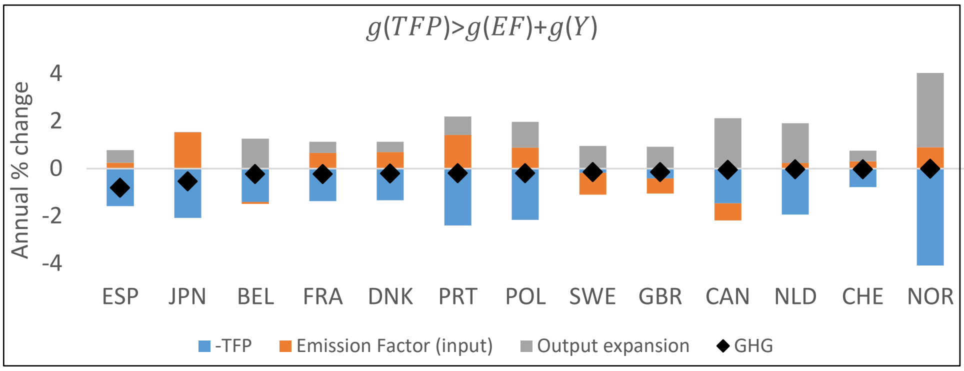
[6] The input and output production data used to construct the TFP index (ERS-USDA, 2023[7]) are also used in the decomposition of the GHG emission changes presented in Section 4, where output changes are presented along with changes in the EF of input use.

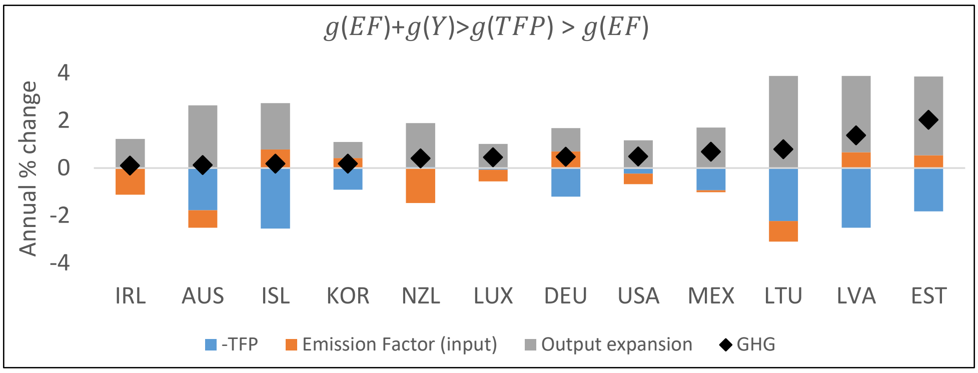
intensification of each emitting input, marked as black triangles. Finally, the sum of these triangles across inputs and within countries equals the change in the EF for aggregate input use shown in Figure 4.3.

Figure 4.3. Decomposition of changes in agricultural non-CO_2 emissions (2006-2015)

a. Countries with an absolute decoupling of emissions from output growth



b. Countries with a relative decoupling of emissions from output growth



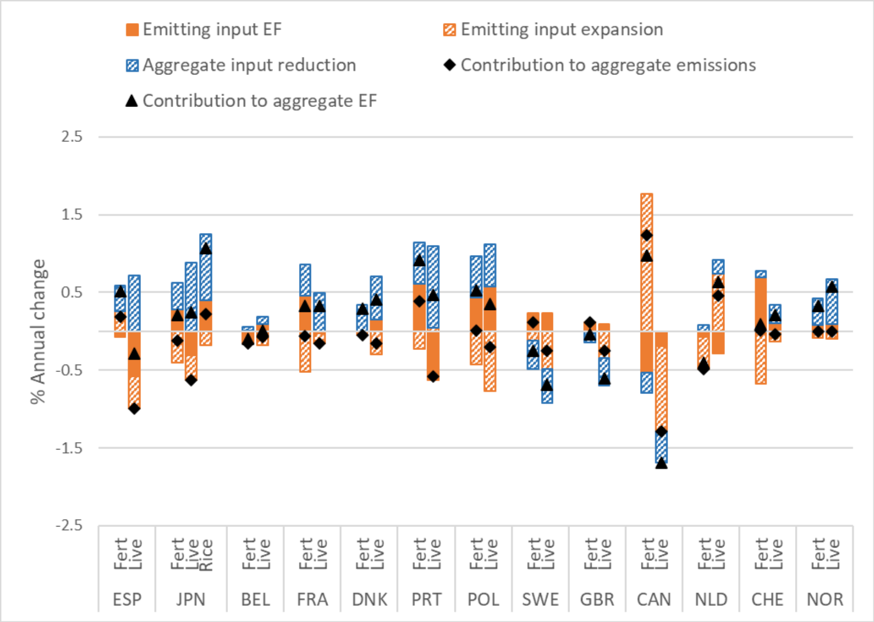
Comparing Figures 4.4a and 4.4b, there are some stark differences in the factors underlying the decoupling of the groups of countries. The most obvious difference is that the absolute decoupling of emissions from output has mainly been driven by input-saving TFP growth (10 of 13, or 77% of countries). In contrast, TFP growth has not been input saving for the majority of countries that achieved relative decoupling, with aggregate input only falling for 25% of these countries. This is shown by the numerous blue bars below the horizontal axis in Figure 4.4.b.

As shown in Figure 4.4a, reduction in overall input use is not always accompanied by reductions in the emitting inputs. Although falling animal stocks underpin the absolute decoupling of emissions from output growth for the vast majority (11 out of 13, or 85%) of countries that achieve this feat. With emissions from livestock also declining for 11 countries. For half of these countries, their livestock-specific EF increases, but not by enough to offset the mitigating effect of the decline in their animal numbers. Thus the stock of animals in all decoupling countries has tended to become more productive, but for many, emissions per head of animals have increased.

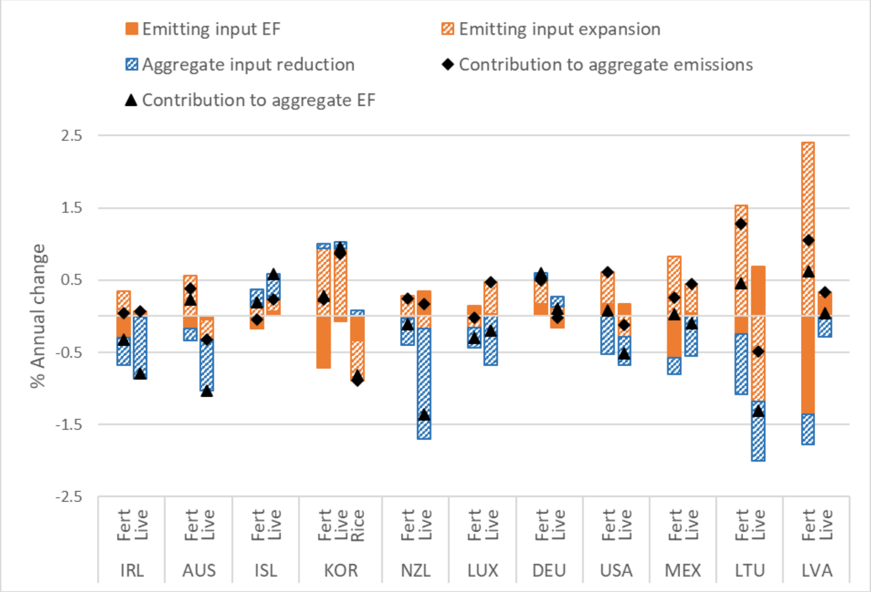
Compared to livestock, fertiliser reductions have contributed less to decoupling emissions from output growth. Fertiliser use declined for the majority of countries with absolute decoupling (9 of 13 countries), but fertiliser emissions increased for 4 out of these 9 countries. This could suggest that changes in the type of fertiliser, how and where it is applied within a country, may be as important as changes in the total amount that is used. As with livestock, there was a relative intensification of fertiliser use for most countries (9 of 13), despite falling fertiliser use, because the aggregate input bundle contracted faster than their emitting inputs.

Figure 4.4. Further decomposition of changes in agricultural non-CO_2 emissions (2006-2015)

a. Countries with an absolute decoupling of emissions from output growth



b. Countries with a relative decoupling of emissions from output growth



Notes: All of the changes with respect to each emitting input are weighted by their respective share of input emissions to allow each item to be added on a common basis. Note that the sign of the aggregate input is changed (hence the term "reduction") to allow: Aggregate input reduction + the emitting input EF + the emitting input expansion = Contribution to aggregate EF. Rice is only included in the figures for those countries in which rice emissions contribute to more than 5% of national agricultural emissions. Livestock emissions correspond to CH_4 and N_2O emissions from enteric fermentation and manure management. Fertiliser emissions correspond to N_2O emissions from agricultural soils, and rice emissions are the CH_4 emissions from paddy rice cultivation.
Estonia is not included in Figure 4.4b to facilitated presentation, because the changes in its variables are significantly larger than for the other countries, causing the bars for these other countries to be too vertically compressed.
Source: The aggregate livestock, fertiliser and rice inputs come from the ERS-USDA (2023[7]) TFP dataset. Livestock is based on farm inventories of livestock and poultry, aggregated as Standard Livestock Units. Fertiliser is calculated based on Total N, P_2O_5, K_2O nutrients from inorganic fertilizers and N from organic fertilizers applied to soils, in metric tons. The rice input was calculated based on the irrigated area of paddy rice. The GHG emissions were taken from the OECD AEI database.

For the countries that achieved absolute decoupling alongside rising aggregate input use (United Kingdom, Sweden, Canada), TFP growth has been dominated by an expansion in output rather than a reduction of input. Despite this, these countries have reduced their overall emissions, by reducing their animal stocks and emissions, despite increasing their fertiliser emissions.

Turning to the countries that have achieved relative decoupling (Figure 4.4b), TFP growth has been tended to be accompanied by an increase in overall input, as well as an increase in emitting inputs. Although fertiliser use increased for a greater share of these countries than livestock (92% and 58%, respectively), and their emission increases have also been slightly dominated by fertiliser use. Interestingly, a smaller number of countries in this group relatively intensified their input bundle, with respect to livestock, when compared to those countries that achieved absolute decoupling. And the same number in both groups increased their relative intensification of fertiliser use.

4.2. TFP compared with WEP as a measure of productivity and environmental growth performance

In this section, results are presented for a version of the WEP that includes GHG emissions as the only environmental variable, to facilitate comparison of this indicator with the decomposition results presented above.

As explained in Section 2, formulating the WEP indicator as the average of TFP and the emission intensity (EI) of production for a single environmental variable, in this case GHG emissions, gives the following:

$$g(WEP_{EI}) = 0.5\left(\mathrm{g}\left(\frac{Y}{X}\right) - g\left(\frac{GHG}{Y}\right)\right) \tag{12}$$

Which can also be re-expressed as:

$$g(WEP_{EI}) = \mathrm{g}(Y) - 0.5\big(\mathrm{g}(\mathrm{X}) - g(GHG)\big) \tag{13}$$

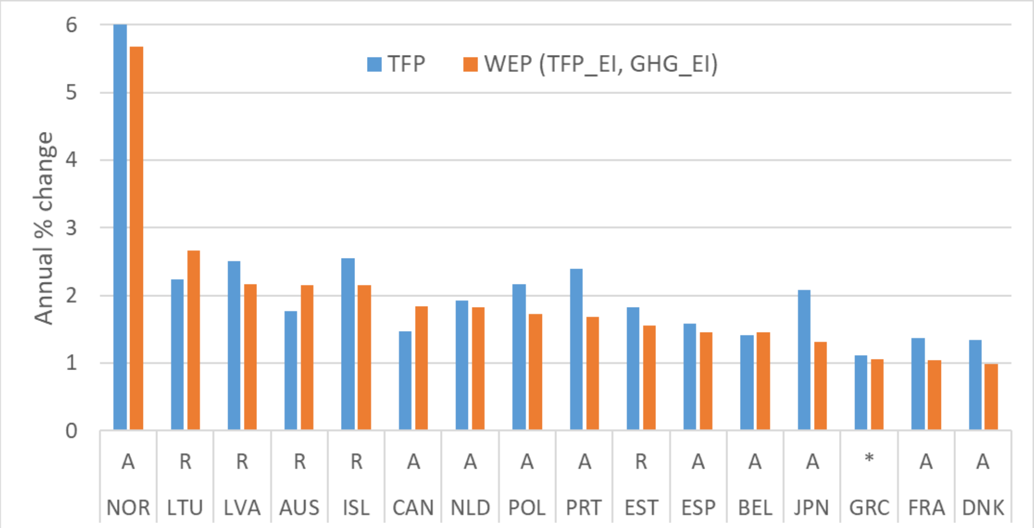
This is a useful formulation, which shows how the intensity-based $\mathrm{WEP}_{\mathrm{EI}}$ indicator can be interpreted as a composite indicator comparable with environmentally-adjusted TFP measure that incorporates environmental flows as inputs, and gives them equal weighting as the standard input bundle. It is a crude approximation in the sense that it sidesteps the complex procedure of assigning weights (e.g. such as using weights for emissions that reflect their marginal social damage costs), with the arbitrary assignment of equal weights. Putting this issue aside, it can be instructive to see how this proxy of environmentally adjusted TFP growth corresponds with standard measures, and whether this comparison yields insights in light of the decomposition results in the preceding section.

With this objective in mind, the standard TFP growth measure, and the $\mathrm{WEP}_{\mathrm{EI}}$ measures are compared side-by-side in Figure 4.5. Countries in the top 50%, with respect to their $\mathrm{WEP}_{\mathrm{EI}}$ growth performance, are shown in Figure 4.5a and the bottom 50% in Figure 4.5b. The countries are also organised in decreasing order of growth performance with respect to $\mathrm{WEP}_{\mathrm{EI}}$. To facilitate comparison with the results from the previous section, the countries with a label ‘A’ appearing above their label are those that achieved an absolute decoupling of emissions from output growth, those with ‘P’ achieved a relative decoupling, and those with ‘*’ did not achieve any form of decoupling.

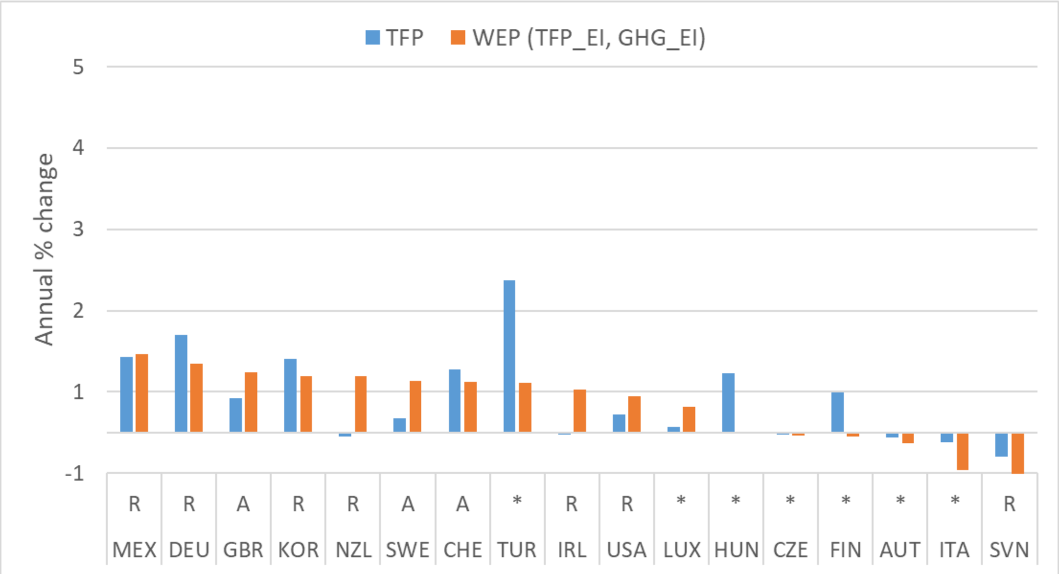
The $\mathrm{WEP}_{\mathrm{EI}}$ scores are broadly consistent with the decoupling findings in that 10 out of the 13 countries which decoupled their emissions from growth, in absolute terms, are captured among the top 50% of growth performers (Figure 4.5a). For 8 of these, joint productivity-sustainability score was lower. The $\mathrm{WEP}_{\mathrm{EI}}$ index also places most of the countries that do not succeed to decouple emissions from growth, in absolute or relative terms, in the last positions with respect to their composite growth performance.

Figure 4.5. TFP growth compared with GHG intensity-based WEP

a. TFP and WEP (TFP, GHG$_{EI}$ and NB$_{EI}$) for the top 50% growth performers



b. Comparison of TFP and WEP 1 (TFP, GHG$_{EI}$ and NB$_{EI}$) for the bottom 50% growth performers



Note: the countries with a label 'A' appearing above their label are those that achieved an absolute decoupling of emissions from output growth, those with 'R' achieved a relative decoupling, and those with '*' did not achieve any form of decoupling.

It is also apparent that upward adjustments in the standard TFP score are possible in situations where emissions either increase or decrease. The same goes for downward adjustments. Positive TFP scores are adjusted downwards in those countries for which their emission reductions are less strong than reductions in the standard input bundle, and when emissions increase faster than inputs. Those countries that achieve some form of decoupling, but have their scores adjusted down (9 out of the 13 countries that achieve absolute decoupling, and 6 out of the 12 countries that achieve relative decoupling), are exactly the same countries that experience a relative intensification of their input bundle with respect to emissions, i.e. an increase in their aggregate EF of input use (discussed in Section 4.1). This reflects the following condition: if $-g\left(\frac{GHG}{Y}\right) > g\left(\frac{Y}{X}\right)$ then $g\left(\frac{GHG}{X}\right) > 0$. As discussed above, this is not important in the context of environmental outcomes, and it also tends to coexist with high TFP growth and emission reductions.

A change from the use of equal weights for emissions and inputs, to a scheme that gives a higher weight to emissions, or vice versa, would not change the direction in which the TFP scores is adjusted. This can be seen with reference to equations (12) and (13), while considering a country for which $-g\left(\frac{GHG}{Y}\right) < g\left(\frac{Y}{X}\right)$. In this case a weight of 1 for emissions and 0 for standard input bundle would cause TFP to adjust to exactly the emission intensity score. Reversing these weights would prevent any adjustment in the TFP score. Thus, the direction of adjustment is robust to the weights used, but the final scores, and ranking of countries based on this score is not.

These conditions and inequalities above also indicate that countries with more output-orientated TFP growth will tend to be favoured by the intensity-based adjustment to TFP, irrespective of whether their emissions rise or fall. This feature of the index can be seen clearly in reference to equation (13), which shows that output receives a relatively stronger weighting than inputs. It is not surprising then to see the upward adjustment in WEP_{EI} relative to TFP, for countries which only relatively decouple their emissions, but which have high TFP growth performance that is output-driven, such as Australia and Lithuania.

There are six countries in which TFP slightly falls. In three of these countries aggregate output expands, but by as much as aggregate input use increases (Austria, Ireland and New Zealand) and for the other three countries, aggregate output falls but by more than aggregate input (Czech Republic, Italy, and Slovenia).

An alternative version of adjusting TFP for emission, also using the simplistic WEP weighting assumptions, would involve combining the change in emissions (with signs reversed) with the output bundle instead. This would share some of the same limitations as the input-based approach above (i.e. of being a relative performance measure), but it would favour countries for which TFP growth has been input-saving and, as shown in Section 4.1, these countries align better with those that have succeeded to lower GHG emissions. Another approach which would provide an equally balanced weighting of outputs, inputs and emissions, is the WEP indicator based on taking the average of TFP and GHG growth rates. The trade-off with this approach is that it is has a less natural interpretation from a production function perspective.

Irrespective of whether or not environmental flows are combined with inputs or outputs, they are relative measures of performance. As such, is it not surprising that there is a mix of top growth performers, with respect to WEP_{EI}, that is not dependent on the type or the extent of decoupling that occurs in Figure 4.5. This reflects the fact that the objective of such indexes is to provide a relative measure that weighs up trade-offs between production and environmental dimensions of performance. At the same time, it does show that composite measures of growth performance need to be combined with additional data sources to explain the dynamics that underlie their results. Even if relative weights, that are consistent with economic theory of production and externalities, were used to weight the inputs and emissions, this requirement would prevail.

Although not shown here, SEP_{EI} scores (based on combining GHG emission intensities with TFP) are also broadly consistent with the decoupling findings, with 10 out of the 13 countries which decoupled their emissions from growth, in absolute terms, also captured among the top 50% of growth performers.

In the following section, different variants of the WEP and SEP composite indicators, combining a broader set of environmental pressure, are explored in depth to complement the above assessments and provide a more complete picture of the joint productivity and environmental growth performance of the sample countries.

4.3. Composite environment — productivity growth indicators

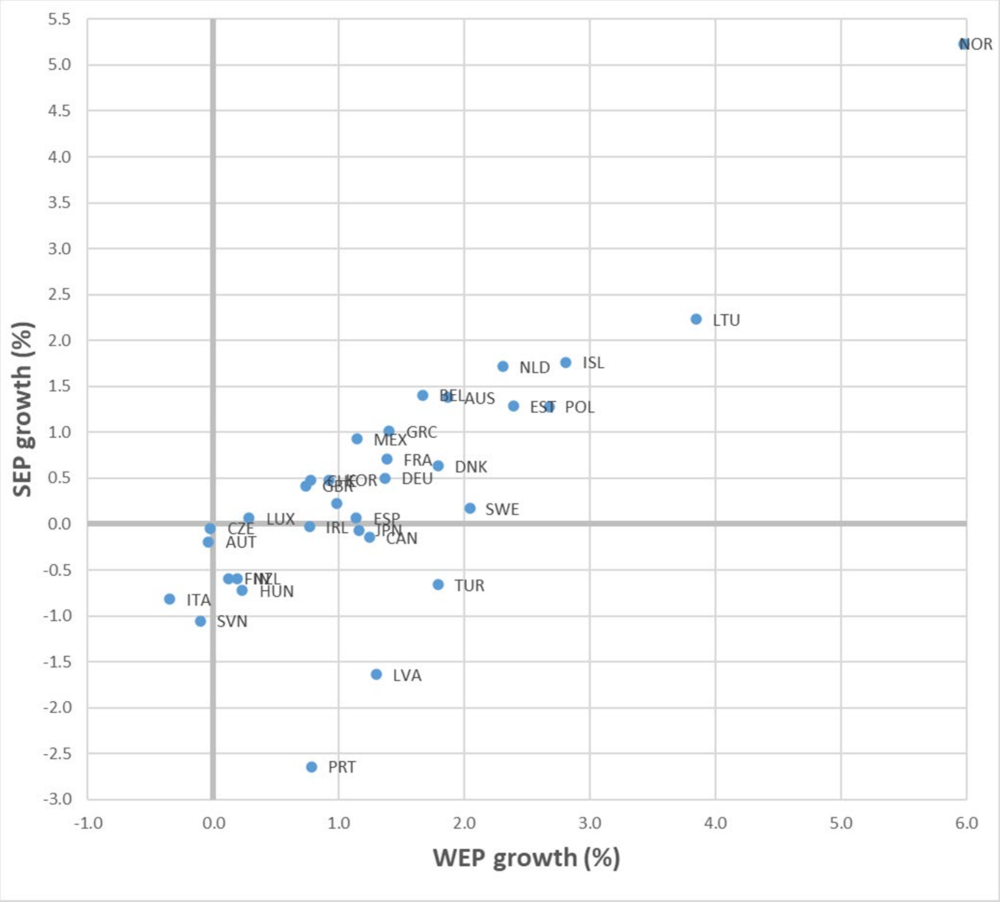
As discussed in Section 2.2, the proposed approach in this paper for aggregation rule of single indicators of productivity and environmental sustainability for different composite indicators is based on the notions of weak and strong sustainability (Lankoski and Thiem, 2020[13]). For the weak environment-productivity (WEP) composite indicator, an aggregation rule is adopted whereby low growth performance on one environmental sustainability dimension can be substituted for by high growth performance on another dimension, and substitution is also allowed between productivity growth and the growth rates for environmental sustainability, that is $g(WEP) = 0.5g(TFP) - 0.5\left(g\left(\frac{GHG}{Y}\right) + g\left(\frac{NB}{Y}\right)\right)$.

For the strong environment-productivity growth (SEP) composite indicator, a strong sustainability rule is adopted, which means that low growth performance in one of the environmental sustainability dimensions cannot be substituted for by high growth performance in other environmental sustainability dimensions and similarly no substitution is allowed between productivity growth and the growth rates for environmental sustainability, that is $g(SEP) = MIN(g(TFP), MIN\left(g\left(\frac{GHG}{Y}\right), g\left(\frac{NB}{Y}\right)\right)$ (Lankoski and Thiem, 2020[13]).

Figure 4.6 shows annual growth rates for SEP and WEP indicators over 2006-2015 based on annual growth rates of productivity and emissions intensity for GHG emissions and N balance. For all countries WEP growth performance is higher than SEP growth performance, since a country can never achieve a better performance under an indicator that is more demanding in its criteria imposed. More than half of the countries (20 out of 33) registered positive annual growth rates with both SEP and WEP indicators over 2006-2015. On this basis, these countries can be considered to be on the right trajectory of improving their joint productivity-environmental growth performance, although there is a wide range of growth rates among these countries. On the other hand, there are four countries that registered negative annual growth rates for both composite indicators. The remaining nine countries achieved positive WEP growth, while suffering a decline in their SEP growth performance. Thus, these countries are improving their sustainability in one or more dimensions, but not in another and moving towards environmentally-adjusted productivity growth performance improvement if the weak composite indicator is adopted, while their growth performance is worsening under the strong criterion.

Figure 4.6. Strong (SEP) versus weak (WEP) composite environment and productivity growth indicators

Annual growth rates of productivity and emissions intensity for GHG emissions and N balance, 2006-2015



While the composite indicators have the virtue of reflecting multiple influences, they also conceal information about the specific drivers of their performance. The results in Figures 4.7a and 4.7b, which show the top 25% and bottom 25% of growth performers with respect to WEP, provide a useful basis upon which to unpack the underlying drivers of the composite WEP growth performance. Note that the term “growth performers” here is used with respect to growth rates and does not necessarily reflect performance in terms of levels. Note also that GHG and NB are reversed and thus show reductions in Figures 4.7a and 4.7b. All top growth performers (Figure 4.7a) have increased TFP and reduced their nitrogen surpluses (NB) and GHG emissions. Among top WEP growth performers good performance tends to be dominated by different elements of composite indicator. For example, TFP growth for Sweden is only 0.2%, but it is compensated by large reductions in its nitrogen surplus. Norway’s good growth performance is driven by strong TFP growth (6.1%) accompanied with large reductions of GHG emissions and NB.

TFP growth is low or negative for most of the bottom 25% of growth performers with respect to WEP growth (Figure 4.7b). For most of them, either GHG emissions or NB or both have increased, causing either a weak or negtive overall WEP growth performance of the agriculture sector in these countries.

Figure 4.8 shows annual change of TFP, output, inputs, livestock, nitrogen fertiliser and manure nitrogen for top growth performers of WEP.[7] TFP, output, inputs and livestock come from the USDA data for TFP accounting, while nitrogen fertiliser and manure nitrogen come from OECD AEIs database. Annual changes in livestock numbers, nitrogen fertiliser and manure nitrogen reflect changes in emitting inputs, while changes in outputs and inputs reflect whether TFP growth has been output expanding or input contracting. In Norway, strong TFP growth has expanded output and reduced inputs, while there has been only small changes in emitting inputs. In Lithuania, output growth has been larger than input growth and there has been changes in emitting input bundle so that livestock, and thus manure nitrogen, has fallen and chemical nitrogen fertiliser has increased. Also, in Poland there have been changes in emitting input bundle so that livestock numbers and manure nitrogen has decreased while nitrogen fertiliser has increased only slightly. In Iceland emitting input bundle changes have been opposite to that of Lithuania and Poland as there has been a slight increase in livestock and manure nitrogen and a reduction in nitrogen fertiliser. Although livestock numbers have increased in the Netherlands manure nitrogen has decreased, which may be explained by changes in feeding practices and diets as well as composition of livestock.

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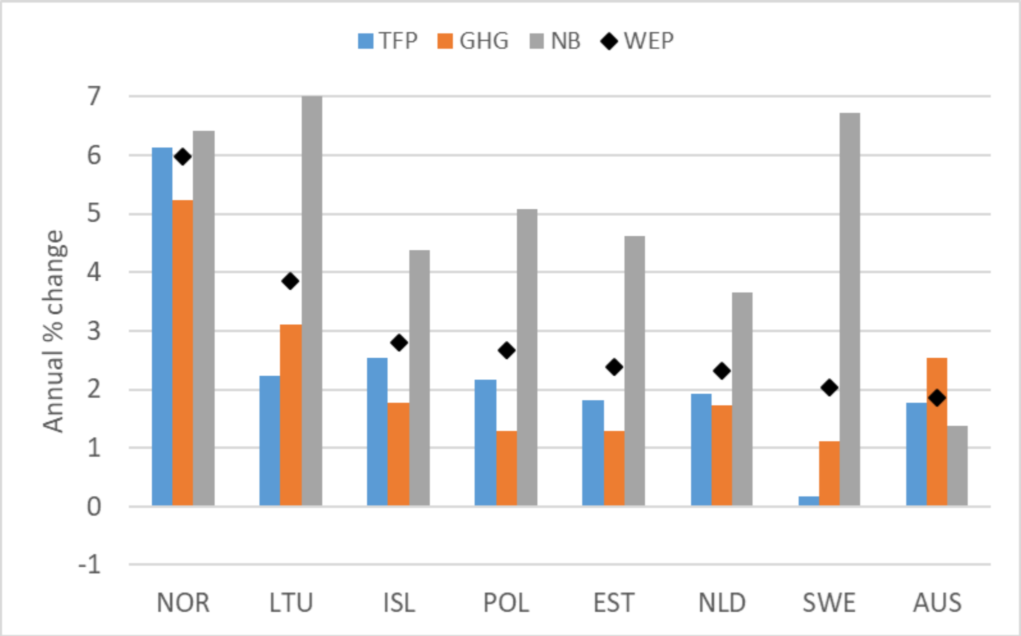
[7] Since the same group of countries is performing well in terms of WEP and SEP growth, numbers are only presented for the top 25% growth performers in terms of WEP. And since the same group of countries are the bottom 25% of growth performers under both WEP and SEP indicators, numbers are only presented for the bottom 25% growth performers of SEP.

Figure 4.7. WEP annual growth and its elements for top 25% and bottom 25% growth performers (2006-2015) (GHG and NB are reversed and thus show reductions)

a. Top 25% growth performers of WEP (2006-2015) (GHG and NB are reversed and thus show reductions)



b. Bottom 25% growth performers of WEP (2006-2015) (GHG and NB are reversed and thus show reductions)

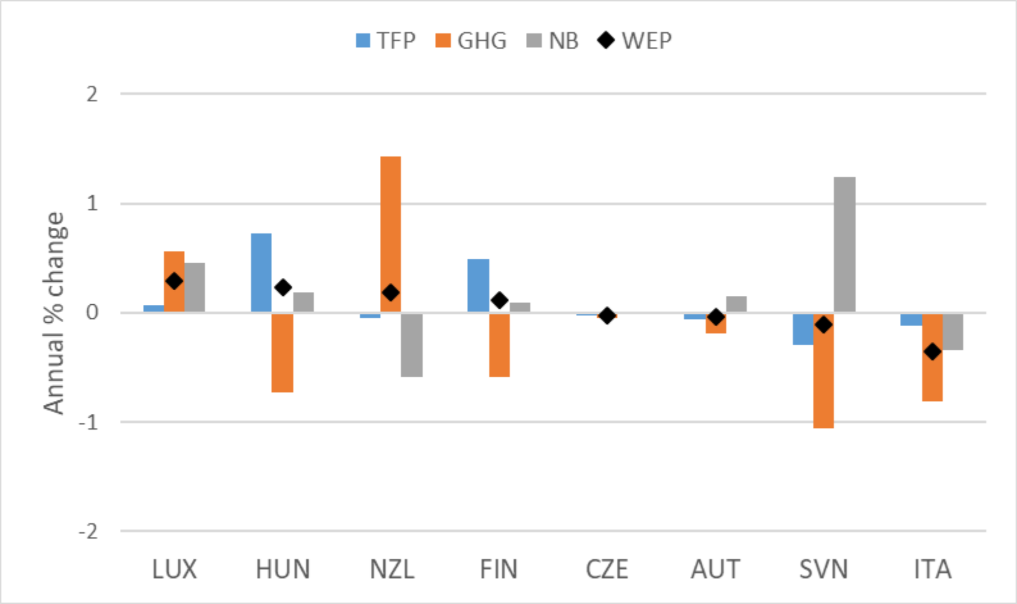
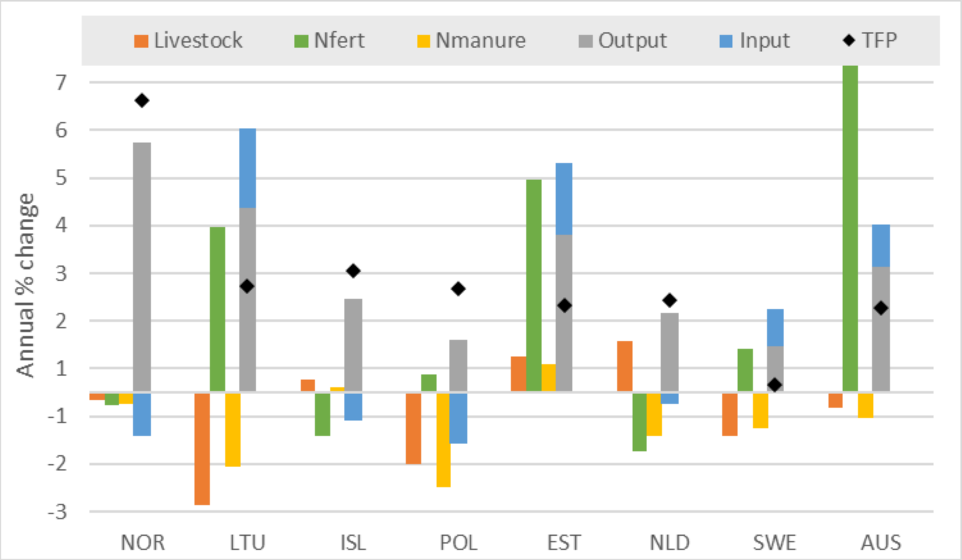


Figure 4.8. Annual change of TFP, output, inputs, livestock, nitrogen fertiliser, and manure nitrogen for top 25% growth performers of WEP (2006-2015)

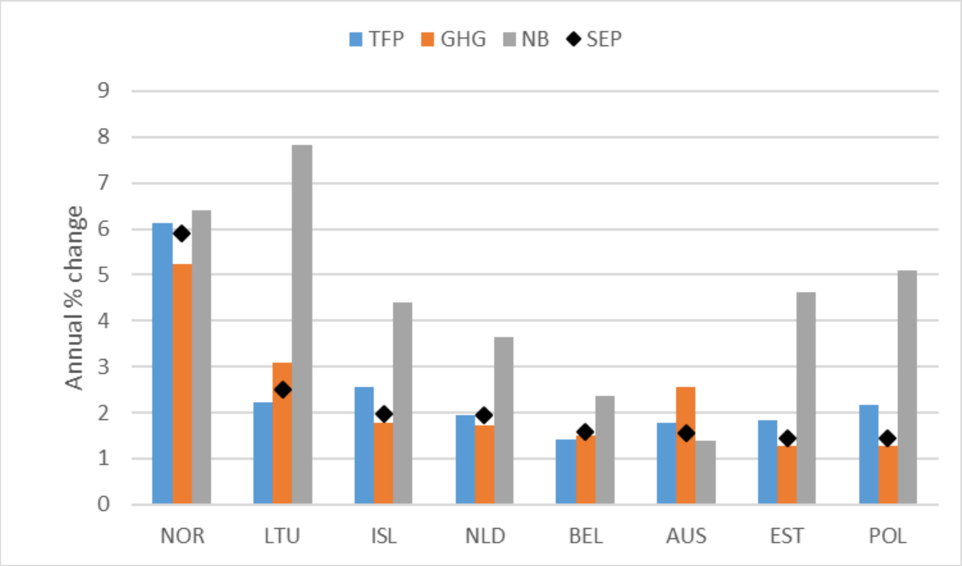


Figures 4.9a and 4.9b show top 25% and bottom 25% growth performers with respect to SEP over 2006-2015. For each country the lowest performing indicator determines its SEP performance. Note that GHG and NB are reversed and thus show reductions in Figures 4.9a and 4.9b. Among the top 25% growth performers of SEP the highest performing country is Norway. Its lowest performing indicator is GHG reduction and thus its SEP growth performance is given by GHG reduction performance. For most of countries the lowest performing indicator is GHG emissions reduction and only in the case of Australia reduction of nitrogen balance determines SEP growth performance. SEP growth rate is negative for all countries among bottom 25% growth performers and GHG emissions reduction or NB tend to set the tone, GHG emissions increase determining the rate of negate SEP growth performance for five out of eight countries, with NB increases setting the rate of negative growth performance for the remaining three countries.

Figure 4.10 shows annual change of TFP, output, inputs, livestock, nitrogen fertiliser and manure nitrogen for bottom 25% growth performers of SEP. Annual changes in livestock numbers, nitrogen fertiliser and manure nitrogen reflect changes in emitting inputs, while changes in outputs and inputs reflect whether TFP growth has been output expanding or input contracting. In Finland both output and inputs have decreased and there has been small reduction in emitting inputs although changes in manure nitrogen have been very small. There has been changes in emitting input bundle in New Zealand so that both livestock and manure nitrogen have decreased while nitrogen fertiliser has increased. In Türkiye all emitting input have increased with livestock and manure nitrogen increasing more than nitrogen fertiliser. In the case of Latvia nitrogen fertiliser use has increased significantly (7%) while there have been only slight changes in another emitting inputs over 2006-2015.

Figure 4.9. SEP annual growth and its elements for top 25% and bottom 25% growth performers (2006-2015) (GHG and NB reversed and thus show reductions)

a. Top 25% growth performers of SEP (GHG and NB are reversed and thus show reductions)



b. Bottom 25% growth performers of SEP (GHG and NB are reversed and thus show reductions)

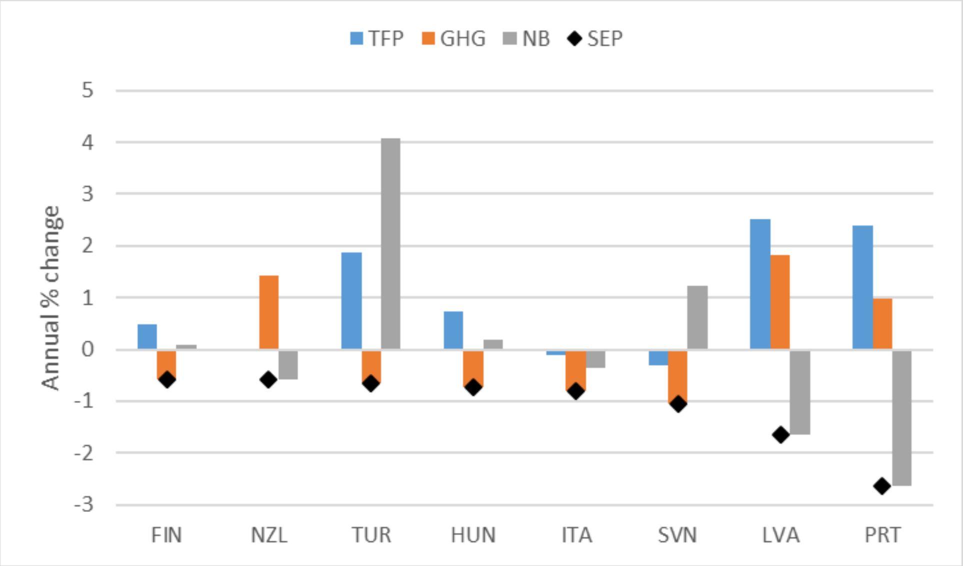


Figure 4.10. Annual change of TFP, output, inputs, livestock, nitrogen fertiliser, and manure nitrogen for bottom 25% growth performers of SEP (2006-2015)

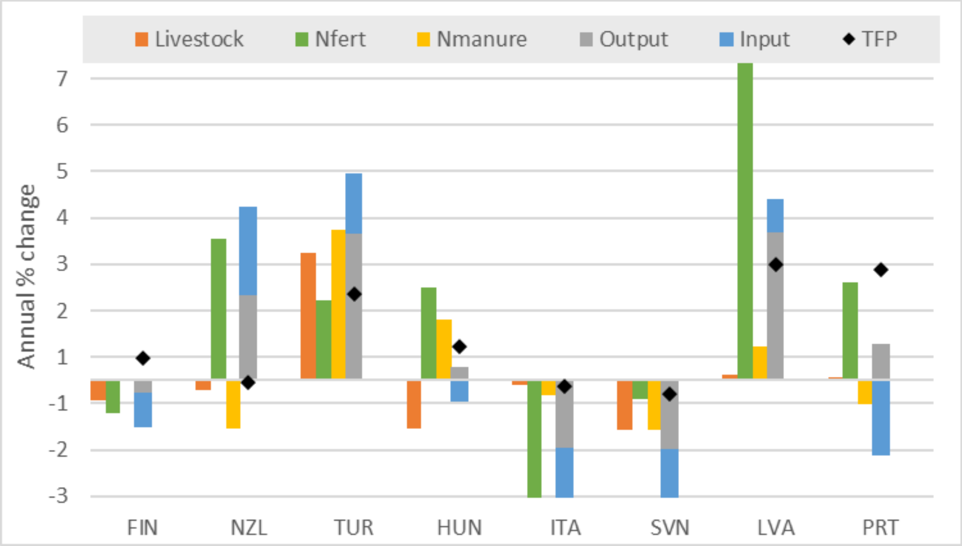


Table 4.1 provides results from a sensitivity analysis to test the stability of country rankings under different weighting assumptions for three dimensions (TFP, GHG and NB) of WEP annual growth composite indicator (for details see Annex A Table A A.1. and Figure A A.1). The aim of the sensitivity analysis is to test the robustness of the WEP composite indicator under different weighting assumptions. To this end, Spearman rank correlation coefficient (r_s) is calculated, which measures the correlation between two ranked variables (based on differences in ranks between paired data). It can be any value from -1 to 1 and the closer it is to -1 or 1, the stronger the monotonic (increasing or decreasing) relationship between paired ranks.

Table 4.1. WEP growth: sensitivity of country ranking to different weighting assumptions

	"Equal weighting" TFP = 0.333; GHG=0.333: NB=0.333	"TFP weighted" TFP = 0.75; GHG=0.125: NB=0.125	"Environment weighted" TFP = 0.25; GHG=0.375: NB=0.375
"Base case weights" TFP = 0.5; GHG=0.25: NB=0.25	Statistically significant very strong, positive correlation (r_s=0.970, p =0.001)	Statistically significant very strong, positive correlation (r_s=0.919, p =0.001)	Statistically significant very strong, positive correlation (r_s=0.940, p =0.001)

Note: Sample size 33 countries.

The results from sensitivity analysis indicate that the country ranking based on the WEP growth composite indicator is highly robust with respect to different weighting assumptions of the three dimensions of the composite indicator.

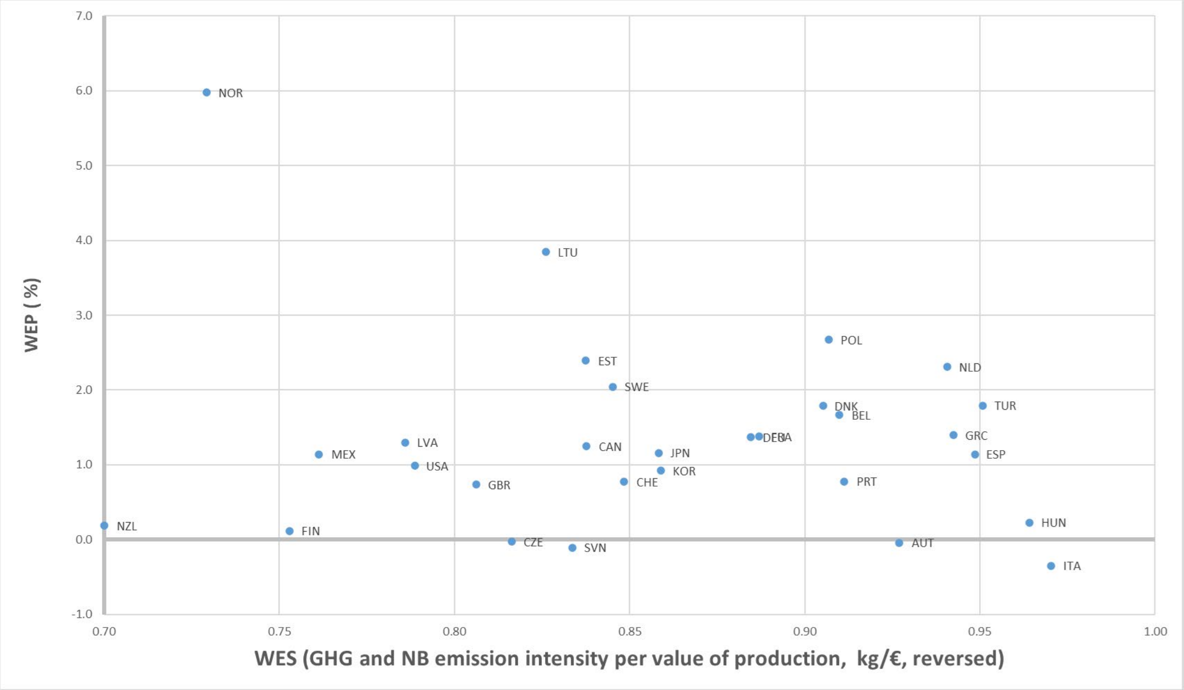
4.4. Composite WEP growth indicator versus composite indicator of weak environmental sustainability

A complementary set of indicators are used to illustrate whether countries that perform well with respect to weak environment-productivity growth also perform well with respect to the level of their weak environmental sustainability performance. These weak environmental sustainability (WES) indicators use the same aggregation rule of weak sustainability, but only focus on emission intensity levels, i.e. GHG emissions or nitrogen balance per ha and GHG emissions or nitrogen balance per value of production.

Deriving these environmental sustainability indicators based on levels (GHG and NB kg per ha or GHG and NB kg per value of production) requires prior data normalisation to make the individual environmental indicators comparable. The min-max method was used for this purpose. It considers the whole range of values (covering each sample country and year) in the distribution of a given environmental indicator as a reference, so that values closer to the maximum value are considered as "good" performance and those closer to the minimum value as "poor" performance. These composite indicators are bounded between 0 and 1, where 0 indicates worst performance and 1 best performance.

Figure 4.11 provides a comparison of the emissions intensity based composite indicator of weak environment-productivity growth rate (WEP: TFP, GHG and NB) with an emissions intensity based composite indicator of weak environmental sustainability (WES: GHG and NB).

Figure 4.11. Emissions intensity per value of production: comparison of a weak environment-productivity growth (WEP) with a weak environmental sustainability (WES) performance level

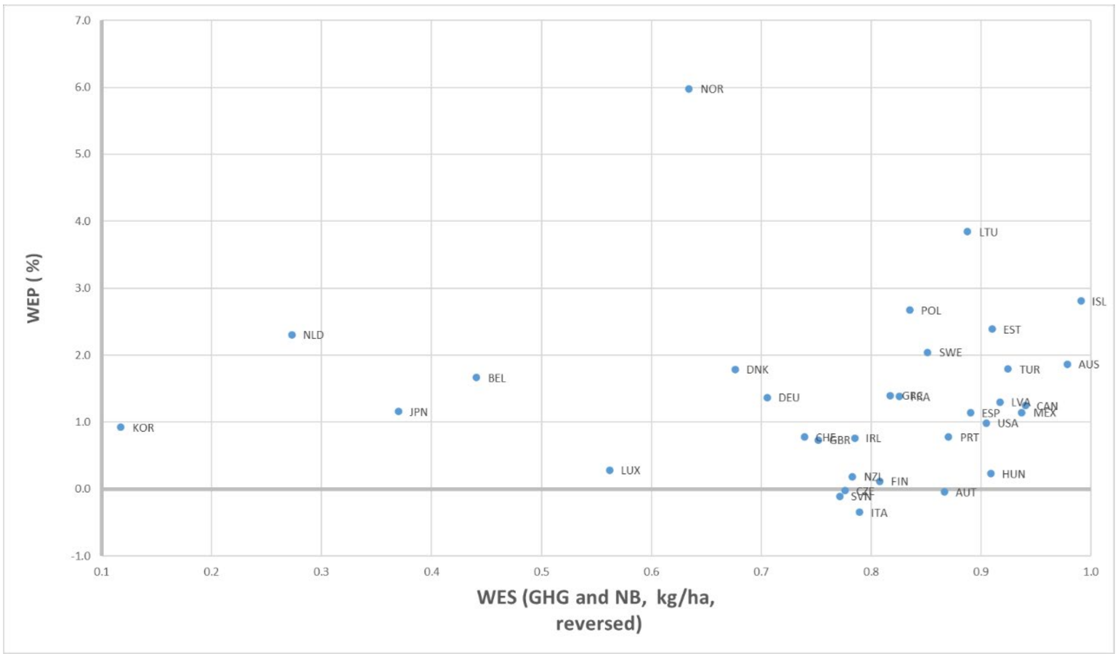


Countries located close to the upper-right corner perform well, as they are increasing their environmentally-adjusted productivity growth while at the same time having a high level of environmental sustainability performance, based on emissions intensity. Many countries have relatively modest growth rates of WEP while they perform well with respect to a WES criterion. But the top growth performers under WEP (Norway, Lithuania, Iceland, Poland, and Estonia) are a different group of countries than those performing well with respect to WES (Italy, Hungary, Türkiye, Spain, and Greece) in the reference period.

Figure 4.12. provides a comparison of an emissions intensity-based composite indicator of weak environment-productivity growth rates (WEP: TFP, GHG and NB) with a per hectare emissions-based composite indicator of a weak environmental sustainability (WES: GHG and NB). Based on per hectare emissions, best performing countries under weak environmental sustainability are Iceland, Australia, Canada, Mexico, and Türkiye.

Further data observations indicate that there is only a very weak relationship between environmental performance (GHG and NB, kg/ha) at the beginning of the time period analysed in year 2006 and WEP annual growth level over the whole time period (2006-2015). Hence, there is no evidence, for example, that countries which had high levels of emissions at the beginning of the time period would have had higher WEP growth rates, or that countries which already performed well with respect to environmental performance would have had lower WEP growth rates because it would have been more difficult for them to reduce emissions.

Figure 4.12. Comparison of a weak environment-productivity growth (WEP) with a weak environmental sustainability (WES) performance level (kg/ha)



5. Summary of findings on the analysis of environmentally-adjusted productivity

5.1. TFP tends to coincide with improved environmental outcomes

The decomposition analysis in the first part of this report indicates that improved environmental outcomes have tended to coincide with TFP growth. For instance, just over three quarters of the sample countries (25 countries) succeeded in reducing their GHG emission intensity of agricultural production, and all but two of these countries registered TFP growth.

However, the extent of these improvements has tended to depend on the strength and nature of the TFP growth. This can be seen by examining differences in the TFP growth that occurred in two different groups of countries that improved their emissions intensity of production: those that achieved an absolute decoupling of agricultural of GHG emissions from output growth (39% of the sample); and those that achieved a relative decoupling. While both groups of countries lowered their emissions intensity of production, only the first group succeed in reducing their agricultural emissions.

Closer examination of the TFP changes and of its underlying variables also reveals clear differences in the nature of TFP growth between those countries that achieved and absolute versus relative decoupling. For instance, the absolute decoupling of emissions from output has mainly been driven by input-saving TFP growth. These input savings have included a reduced reliance on emitting inputs, which has translated to a fall in GHG emissions, from livestock in particular. Changes in fertiliser use and the associated emissions has been more mixed among these countries. However, input-saving TFP growth has also been accompanied by a saving in emissions from the input bundle as a whole. While this input-saving TFP growth enabled many countries to lower their emissions, it has also come with a relative emission-intensification of their aggregate input bundle, as non-emitting inputs fell faster than emitting inputs.

For the countries that achieved relative decoupling, TFP growth tended to be dominated by output growth rather than reduced input use, as their input use tended to grow along with the associated emissions. This has still helped these countries to lower the emission intensity of their agricultural production (without reducing absolute emissions), which has enabled more food to be produced with less emissions than would otherwise have been possible without these improvements.

5.2. How have countries performed with respect to composite indicators of environment-productivity growth

As shown in the report, a weak environment-productivity growth (WEP) indicator based on the combining of TFP growth and emission intensity of output, with equal weights can be interpreted as a crude TFP measure adjusted for the environment. As such, a WEP indicator, based only on TFP and GHG emission intensities, was compared to standard TFP scores to gain further insights on its suitability as measure of environmentally-adjusted productivity. The WEP scores are broadly consistent with the decoupling coupling findings above, in that most of the countries which decoupled their emissions from growth, in absolute terms, are captured among the top 50% of growth performers.

To this end, different variants of the WEP and SEP composite indicators, combining a broader set of environmental pressures, were explored in depth to provide a more complete picture of the environmentally-adjusted productivity growth performance of the sample countries. More than half of the countries (20 out of 33) registered positive annual growth rates with both SEP and WEP indicators over 2006-2015. On this basis, these countries can be considered to be on the right trajectory of improving their environmentally-adjusted productivity growth performance, although there is a wide range of growth rates among these countries. On the other hand, there are four countries that registered negative annual growth rates for both composite indicators. The remaining nine countries achieved positive WEP growth, while suffering a decline in their SEP growth performance. Thus, these countries are improving their sustainability in one or more dimensions, but not in another and moving towards environmentally-adjusted productivity performance improvement if the weak composite indicator is adopted, while their growth performance is worsening under the strong criterion.

5.3. Proposed future work

Future work is recommended to build on the assessments presented in this report and provide policy makers with an additional insights and evidence with respect to the combined environment-productivity growth performance of the agricultural sector. This could include exploring the impact of agricultural or environmental policies on environmentally-adjusted productivity growth performance. Complementary work to measure environmentally-adjusted TFP using indexes with alternative weighting schemes and calculation methods that fully integrate environment and natural resource sustainability into TFP could also be pursued. Future work could also make use of more recent data and consider more environmental variables, depending on data availability. Finally, the approaches used in this report could also help to support OECD’s ongoing work on reviewing country agricultural policy settings with respect to innovation and environmental sustainability.

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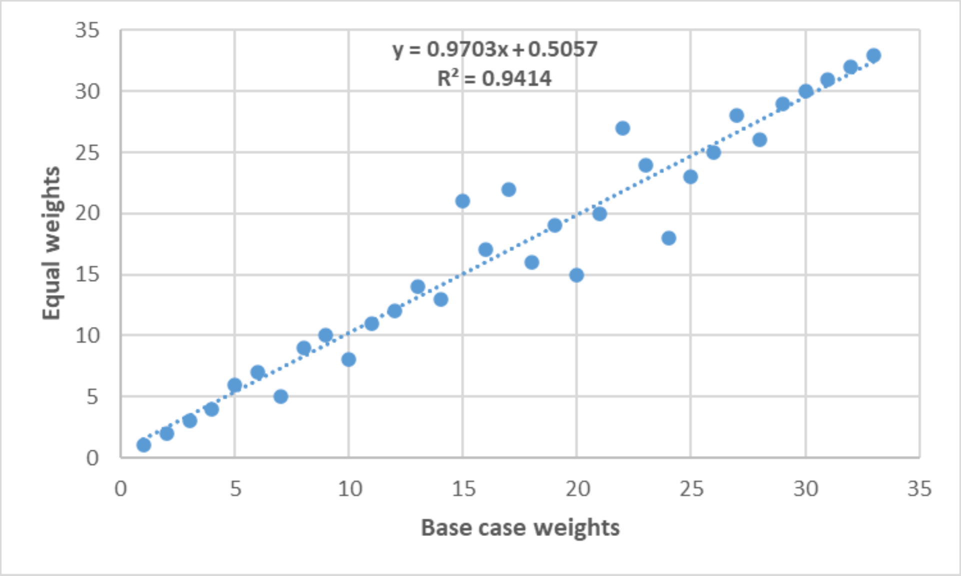
Annex A. Weak environment-productivity growth composite indicator: Country ranks under different weighting schemes

Table A A.1. Country ranks under different weights for dimensions of WEP composite indicator

Country	“Base case weights” TFP = 0.5; GHG='0.25:' NB=0.25	“Equal weighting” TFP = 0.333; GHG='0.333:' NB=0.333	“TFP weighted” TFP = 0.75; GHG='0.125:' NB=0.125	“Environment weighted” TFP = 0.25; GHG='0.375:' NB=0.375
AUS	8	9	9	9
AUT	31	31	31	31
BEL	11	11	13	10
CAN	16	17	16	18
CHE	23	24	22	22
CZE	30	30	30	29
DEU	14	13	17	13
DNK	10	8	12	8
ESP	19	19	15	20
EST	5	6	6	6
FIN	29	29	27	32
FRA	13	14	14	14
GBR	25	23	24	21
GRC	12	12	18	12
HUN	27	28	25	28
IRL	24	18	26	17
ISL	3	3	3	4
ITA	33	33	33	33
JPN	17	22	10	23
KOR	21	20	21	19
LTU	2	2	2	2
LUX	26	25	28	25
LVA	15	21	7	24
MEX	18	16	20	16
NLD	6	7	5	7
NOR	1	1	1	1
NZL	28	26	29	26
POL	4	4	4	5
PRT	22	27	11	30
SVN	32	32	32	27
SWE	7	5	19	3
TUR	9	10	8	11
USA	20	15	23	15

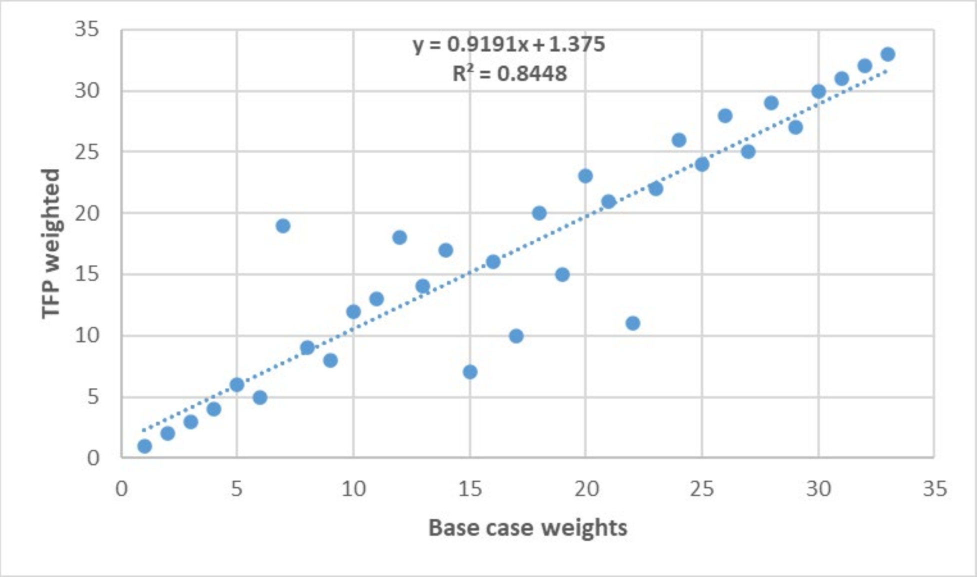
Figure A A.1. Visual representation of the relationship between the ranks

a. Base case weights versus equal weights



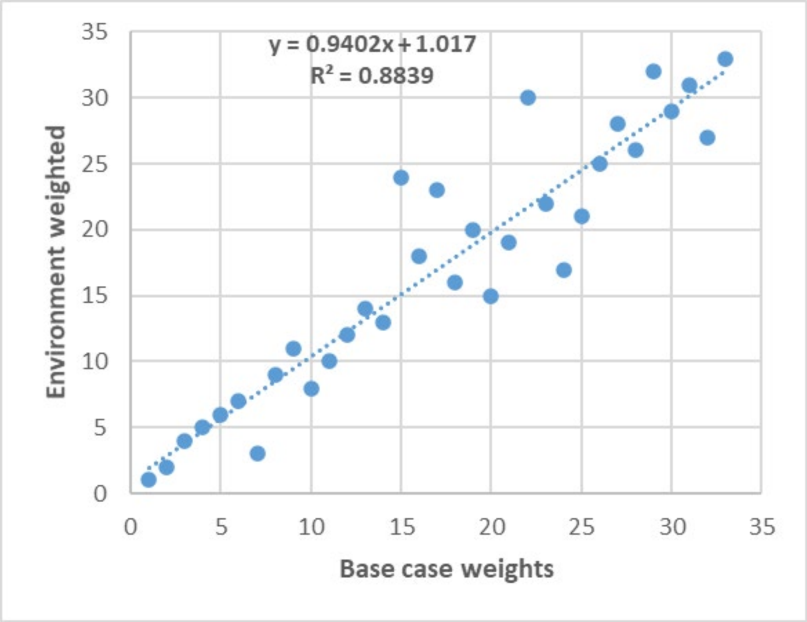
Note: The square root of the Coefficient of Determination (R^2) provides Spearman's rho (0.9703)

b. Base case weights versus TFP weighted



Note: The square root of the Coefficient of Determination (R^2) provides Spearman's rho (0.9191).

c. Base case weights versus environment weighted



Note: The square root of the Coefficient of Determination (R^2) provides Spearman's rho (0.9402).

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Comments are welcome and can be sent to tad.contact@oecd.org.