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Marginal Trade-Offs for Improved Agro-Ecological Efficiency Using Data Envelopment Analysis

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Abstract: Today's agricultural management decisions impact food security and sustainable ecosystems, even when operating with back-to-basic operations. In such endeavors, policymakers usually need a quantitative tool, such as trade-offs margins, to effectively adjust resource consumption or production. This paper applies the weighted slack-based measurement (SBM-DEA) program to 136 developing countries' agricultural performance. First, it finds the current agricultural efficiency and then makes marginal trade-offs on desirable-output variables (such as crop yield and forest area) to see the effective changes in undesirable-output (such as methane and nitrous oxide emissions). The results show that choosing effective marginal trade-offs does not deteriorate the relative efficiency of the decision-making units (DMUs) below the efficient frontier line. Thus, such a method enables the decision-makers to determine the best marginal trade-off points to reach the optimal efficiencies and decide which output factor needs special brainstorming to design effective policy.

Keywords: data envelopment analysis; ecological efficiency; marginal rate; trade-offs

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1. Introduction

Agricultural efficiency makes an important contribution to the country's economy [1]. Efficiency improvements become crucial with the involvement of indirect variables [2], such as forest area, and basic agricultural emissions (even when considering machineless agricultural operations). That is, if we separate the CO_2 emissions since they are connected to so many other things (i.e., machines), agricultural operations still also accompany the methane and nitrous oxide emissions as an indirect cost [3]. Therefore, resource consumption (undesirable) and production (desirable) are the key activities reflecting economic progress. Massive agricultural activity has become a potential contributor to ecological efficiency as it is directly proportional to the forest area and cultivating emissions (global carbon budget 2016 [4]). If it is not carefully planned, it can cause severe environmental problems. Therefore, to achieve higher agricultural efficiency, indirect variables must also be taken into account for real operational evaluation.

Trade-off techniques have been found widely explained theoretically, and their importance has been increased in the agricultural system to foresee the outcomes [5]. For example, a recent study by Ndiaye et al. (2019) [6] uses trade-offs between sorghum and agronomic performance stability. Kanter et al. (2018) [7] evaluates the trade-offs for sustainable developments considering agricultural systems. Conventionally, the trade-off is such an adjustment which gives the maximum output, and to see its effect on other variables when performed on one variable [8]. Akbar et al. [9] presented the conference paper, in which the trade-off has been performed using statistical techniques.

Moreover, finding an effective mathematical program that can be used to calculate the trade-offs is another difficult task. Data envelopment analysis (DEA) is one of the methods that can help perform marginal trade-offs. Mirzaei et al. [10] have used DEA to calculate the marginal rates of substitution to achieve optimal hydroelectric power plants optimal efficiencies. Khoshandam et al. [11] use trade-off balanced to nondiscretionary (ND) factors. Similarly, Atici and Podinovski [12] use DEA to assess the efficiency of the different agricultural units with production trade-offs. Asmild et al. [13] calculate trade-off margins with the elasticity of substitution. In their study, the new thing is that it can take negative and positive values both.

In this study, our analysis contributes in two ways. First, it enables us to bring improvement in the undesirable outputs by performing trade-offs among the desirable outputs. This means we do not have to reduce the inputs (i.e., resources like land and manpower, etc.). Second, it enables us to design better trade-off margins. Such margins do not disturb the relative efficiency of the DMUs below the frontier line but bring upon optimal efficiencies among the weakly efficient DMUs. By this, we mean that the DMUs may have appeared efficient (i.e., on the efficient frontier), but due to slacks in an undesirable output, they are considered weakly efficient. Hence, their efficiency can be further improved to the optimal level with the help of marginal trade-offs.

This study first uses a weighted slack-based measurement (SBM) model to calculate 136 developing countries' efficiency. Then, it calculates the margins, by using the method proposed by Krivonozhko et al. [14], with which the trade-offs can be performed. In the second part (the marginal trade-offs), we consider that the inputs which are at the bottleneck and cannot be decreased or increased further (by the operational manager). Hence, the marginal trade-offs are to be considered only among desirable-outputs to improve the efficiency of undesirable-outputs. The rest of the paper is designed as follows; the next section thoroughly discusses the literature on trade-off methods and its computation with DEA. Section 3 puts forward the applicable model of SBM-DEA and marginal trade-offs, followed by an example. Section 4 discusses the measuring variables and analyzes the results. The conclusion is written in Section 5.

2. Literature

Agriculture industry plays an important role in the socioeconomic freedom (a tool to boost financial activities) and environmental sustainability of the developing countries [15,16]. If we use trade-offs as a method to cope with the optimal efficiency difficulties, the definition of trade-offs must be clear. There is a lot of research variations due to the perceived definition of quantitative trade-off methods. Some use trade-offs as a tool to find an effective balance between efficiency-related variables, for example, see the recent study of Akbar el al. [9], while others consider eliminating the trade-offs for sustainable and efficient performance, for example, Gružauskas et al. [17] and Shahbazpour and Seidel [18]. Our work adheres to the previous definition of trade-off, but to find the quantitative margins with which the trade-offs should be performed is rather challenging and new to the literature.

On the contrary, the method selection of trade-offs is also crucial, because it depends on the operational plans and gains. Therefore, we divide our literature in the following two parts. The first part discusses the recent developments in the agricultural efficiency specifically concerning emissions, which not only portrays its importance but also validates our contribution in the existing literature of the agriculture energy efficiency. The second part assesses the best fit of DEA to perform the quantitative trade-offs.

2.1. Developments in the Agro-Ecological Efficiency

Immense literature with considerable effective outcomes has been found for the ecological performance in agricultural operations. The most recent work of Pratt et al. (2020) [19] researched the opportunities where geosphere can support the agricultural system across four key challenges. One of their four findings is to mitigate the emissions of carbon dioxide CO_2, methane, and nitrous oxide N_2O. An interesting fact indicated is that the increasing geological inputs could increase footprints in an agricultural system. Akbar et al. (2020) [20] work on the reduction of the CO_2 up to the sustainable level in an agro-ecological efficiency. They find the important factors affecting agro-ecological growth, such as planting structure, value-added per capita, and scale management etcetera. Bosco et al. [21] focus on the emissions from agriculture cultivation during seasonal crop rotations. They perform trade-offs between the greenhouse gases and the crop productivity within the three cropping systems (GHG).

Most importantly, they show that the organic conversion system does not really contribute to GHG mitigation during crop rotations. Shen et al. [22] work on the methane and nitrous oxide emissions from crops and animals of 69 municipalities. The results show that the direct N_2O emissions are larger than indirect emissions, and the maximum N_2O emissions were found to be from synthetic fertilizers. Same is the work by Yue et al. [23] and Tang et al. [24] but considering China's long-term fertilizer management. On the other hand, Audet et al. [25] present that important sources of N_2O emissions include forest streams, which is equivalent to 25% of the agricultural N_2O emissions in Sweden. Wysocka et al. [26] statistically analyze the N_2O and methane emissions from regional agriculture and suggest that best management practice can reduce the burden of environmental emission which may enhance the profitability. In their later work [27], they found that farmers may be asked to find different niches which are profitable and less environmentally troublesome (including GHG). There is a huge pile of literature as we move backward in the literature, however, the work of Zanist et al. [28] differs in a sense that they spot the indirect factors of N_2O emissions from headwater streams and the drain fields of agriculture.

2.2. Quantitative Trade-Offs with Data Envelopment Analysis

A plethora of data envelopment analysis (DEA) studies is found in the decision-making units (DMUs). Like many other sectors (banks, hotels, hospitals, and production firms etc.), it has been widely used in the agricultural efficiencies. However, the DEA with trade-off application is rather scarce, and there is further room available for improvement and techniques. There are several DEA studies which contributed to the concept of quantitative trade-offs. Most of them used trade-off for a single measure, i.e., only among two variables, when a change is brought to one variable to see another variable's effect. Rosen et al. [29] solved the balance between two variables in DEA on the effective boundary. Sueyoshi and Goto [30] used the production method to calculate the trade-off effect, in which a set of variables weighed between them. They use nondiscretionary factors to expand the work of substitution rates. Research by Huang et al. [31] proposed a general method, which changed the rate of change from output to input along the production set's efficient boundary. Emrouznejad and Yang (2018) [32] revalidated the work of Cooper et al. [33], modified the basic additive DEA model, and used the slack of the result to design an effective trade-off and marginal rate of substitution. Chang et al. [34] also used trade-offs to evaluate the environmental efficiency of transportation. They found better performance considering the greenhouse gases emissions. Watto and Mugera [35] used a trade-off model to estimate the effective use of groundwater. Again, the slacks were used. It turns out that water buyers are not as efficient as pipeline owners.

As mentioned earlier, the above-mentioned work considered the trade-offs among the two variables only. However, our work is related to multivariable trade-off. In our further literature research, there is not much that deals with multiple variables except the few to the best of our knowledge. The work of Miller et al. (2019) [36], tailed by the findings of Mirzaei et al. [10], used elasticity of substitution between input variables. Their paper provide derivatives and parsimonious methods for estimation using DEA. Akbar et al. [37] define the further types of trade-offs among multiple factors and the way to improve the trade-offs. This was followed by their advanced work of identifying the trade-offs using the DEA programs [9] and the statistical methods of performing multivariable trade-offs, conceptually [9]. Considering the work of Miller et al. (2019), we can use support surface bonding with effective boundary points to define different trade-off margins. Such margins do not lose the relative efficiency of the unimproved DMU, but rather promote the weakly efficient DMUs to the best efficiency point. This paper uses the same methodology on rather complex multiple variables with a large amount of data. However, it should be noted that the piecewise linear boundary in DEA technology is not clear in some cases, and the marginal trade-offs of one or more variables can only use a smaller substitution.

3. Model

In this section, we first explain a little the basic model of the slack-based measurement (SBM), then the weighted SBM model is described, which is mainly used for the efficiency measurement of the decision-making units (DMUs), i.e., countries in our case. Next, we explain the trade-off program followed by the marginal trade-offs.

3.1. Slack Based Measurement of DEA

We present here the SBM model to be used with undesirable outputs. The basic model was presented by Ton (2001) [38]. It has two properties, and one is that its unit of the measure remains the same, and another is that it has a monotonous decrease. The following basic program is developed by Tone.

$$\rho = \left(\frac{1}{m}\sum_{i=1}^{m}\frac{x_{io}-s_i^-}{x_{io}}\right)\left(\frac{1}{s}\sum_{r=1}^{s}\frac{y_{ro}+s_r^+}{y_{ro}}\right)^{-1}. \tag{1}$$

The ratio $(x_{io}-s_i^-)/x_{io}$ gauges the virtual reduction rate of the input variable i; therefore, $(1/m)\sum(x_{io}-s_i^-)/x_{io}$ corresponds to the reduction rate of inputs of the mean proportion. Similarly, the term $(y_{ro}-s_r^+)/y_{ro}$ evaluates the proportional expansion rate of the output r and $(1/s)\sum(y_{ro}+s_r^+)/y_{ro}$ is the mean proportional rate of output. Further, the inputs and outputs can be assigned weights as follows:

$$\rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m} w_i^- s_i^-/x_{io}}{1+\frac{1}{s}\sum_{r=1}^{s} w_r^+ s_r^+/y_{ro}}, \tag{2}$$

where:
$\rho =$ efficiency;
$x_{io} =$ input variable of unit i;
$y_{ro} =$ output variable with r;
$s^- =$ excesses in inputs;
$s^+ =$ shortages in outputs; and
$r =$ growth rate.

This choice of weights with $\sum_{i=1}^{m} w_i^- = m$ and $\sum_{r=1}^{s} w_r^+ = s$ reflect the importance of the input i output r, them being proportional to its average amplitude. Generally, DEA allows more production as outputs with taking relatively fewer inputs, but the further expansion in the SBM program includes the undesirable outputs. The evaluation of the undesirable outputs is different since it also indicates an excessive amount indicating deficiencies. Seiford and Zhu [39] presented the original DEA model in 2002 and used desirable and undesirable output methods. Later, the trade-off (relaxation values) based calculations were modified by Cooper et al. [40]. This method solves the environmental inefficiency by considering undesirable output (such as GHG). One method is to convert the undesired output values to the desired values, but this may result in a misrepresentation of the effective boundary and, therefore, result in a different efficiency score. We, therefore, adopt the undesirable values for our calculations.

Suppose that the n DMUs, each having three factors, are input x, desirable output y^g, and undesirable output y^b, represented by three vectors $x \in R^m$, $y^g \in R^{s_1}$, and $y^b \in R^{s_2}$, respectively. The matrices X, Y^g, and Y^b are defined as follows:

$$X = [x_1 \quad \cdots \quad x_n] \in R^{m\times n}, \tag{3}$$

$$Y^g = [y_1^g \quad \cdots \quad y_n^g] \in R^{n\times s_1}, \tag{4}$$

$$Y^b = [y_1^b \quad \cdots \quad y_n^b] \in R^{n\times s_2}. \tag{5}$$

Let us assume that $X > 0$, $Y^g > 0$, and $Y^b > 0$, then the production possibility set as:

$$P = \{(x, y^g, y^b) | x \geq X\delta, y^g \leq Y^g\delta, y^b \geq Y^b\delta, \delta \geq 0\}, \tag{6}$$

As per the definition of the SBM-undesirable output model, a DMU_o (x_0, y_o^g, y_o^b) is efficient in the presence of an undesirable output if there is no vector $(x, y^g, y^b) \in P$, such that $x_0 \geq x, y_o^g \leq y^g, y_o^b \geq y^b$. Following this definition, in the case of one input, one good output, and one bad output, the modified SBM of William Cooper et al. is as follows:

$$\rho^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)}. \tag{7}$$

Subjected to

$$x_o = X\delta + s^-, \tag{8}$$

$$y_o^b = Y^b\delta + s^b, \tag{9}$$

$$y_o^g = Y^g\delta - s^g, \tag{10}$$

$$\therefore s^-, s^g, s^b, \delta \geq 0. \tag{11}$$

The function is strictly decreasing when $s_i^- (\forall i)$, $s_r^g (\forall r)$ and $s_r^b (\forall r)$, and the objective value must be satisfied with the condition $0 < \rho^* \leq 1$. The vector $s^- \in R^m$ indicates the excesses in the inputs and $s^b \in R^{s_2}$ indicates to the excesses in undesirable outputs, while $s^g \in R^{s_1}$ represents shortages in desirable outputs. In the presence of the undesired output, if DMU_o (a decision-making unit) has optimal efficiency $\rho^* = 1$, or we can say if the slacks are equal to zero, i.e., $s^-, s^g, s^b = 0$, then the DMU_o is called efficient. If the DMU_o is inefficienct or if it has low efficiency, i.e., $\rho^* < 1$, then it can be improved by reducing excessive inputs and excessive undesirable outputs or increasing the desirable output. The function ρ^* is a decreasing function, where s_i^- / x_{io} and $s_{r/}^b y_{ro}^b$ are bounded by 1, whereas s_r^g / y_{ro}^g is unbounded.

Now, as this paper follows, the above program (7) can be assigned with weights. The weighted ratio of desirable to undesirable output can also be implemented on the SBM-undesirable output model.

$$\rho^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{w_i^- s_i^-}{x_{io}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{w_r^g s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{w_r^b s_r^b}{y_{ro}^b}\right)}, \tag{12}$$

where w_i^-, w_r^g, and w_r^b represent the weights to the input i, desirable outputs r, and undesirable outputs r, respectively. Additionally, $\sum_{i=1}^{m} w_i^- = m$, $w_i^- \geq 0$ $(\forall i)$, $\sum_{r=1}^{s_1} w_r^g + \sum_{r=1}^{s_2} w_r^b = s_1 + s_2$, $w_r^g \geq 0$ $(\forall r)$, and $w_r^b \geq 0$ $(\forall r)$.

3.2. Model for Trade-Off Balances

Mathematically, the marginal rates (MR) are used to calculate the margins with which trade-offs can be performed. In the multidimensional input and output space, the

DEA production possibility set can evaluate agricultural performance without losing mathematical objectivity. By considering a general process, the marginal substitution rate is used, in which the input vector $x = x_1, \ldots, x_m \in R_+^m$ is consumed by the output vector $y = y_1, \ldots, y_s \in R_+^s$. The group of $n\text{DMU}_j$: $j = 1, \ldots, n$ is represented by trade-off vectors $z_j = \left(x_j, y_j\right)^t$, where $x_j = x_{1j}, \ldots, x_{mj}$ and $y_j = y_{1j}, \ldots, y_{sj}$ are positive vectors and are above zero.

Suppose that the efficient boundary is $F(x, y) = 0$, we can assume that

$$\begin{aligned} \frac{\delta F(x,y)}{\delta x_i} &< 0 \qquad i = 1, \ldots, m \\ \frac{\delta F(x,y)}{\delta y_r} &< 0 \qquad r = 1, \ldots, s \end{aligned} \tag{13}$$

Assuming that $(x,\ y)$ is differentiable. Let $z_o = x_o, y_o$ be the efficient frontier; i.e., $F(z_o) = F(x_o, y_o = 0)$. By definition, the trade-off τ at the efficient boundary is as follows:

$$\begin{aligned} \tau_{jk}^{+}(z_0) &= \left(\frac{\delta z_{jo}}{\delta z_{ko}}\right)_{z_0^+} = \lim_{h \to 0^+} \frac{f_j(z_{1o}, \ldots, z_{ko} + h, \ldots, z_{m+so})}{h} \\ \tau_{jk}^{-}(z_0) &= \left(\frac{\delta z_{jo}}{\delta z_{ko}}\right)_{z_0^-} = \lim_{h \to 0^-} \frac{f_j(z_{1o}, \ldots, z_{ko} + h, \ldots, z_{m+so})}{h} \end{aligned} \tag{14}$$

Asmild et al. [13] gave a program for calculating the trade-off from j to k as mentioned below:

$$\tau_{jk}^{+}(z_0) = \frac{z_{jo}^{*} - z_{jo}}{h} \tag{15}$$

where z_{jo}^{*} is the optimal, efficient point, h is a positive number, and it is the solution to the following linear program:

$$\begin{aligned} &\max z_{jo}^{*} \\ \text{s.t.} &\sum_{t=1}^{n} \delta_t z_{lt} \geq z_{lo} \qquad l \neq j, k \\ &\sum_{t=1}^{n} \delta_t z_{jt} \geq z_{jo}^{*} \\ &\sum_{t=1}^{n} \delta_t z_{kt} \geq z_{ko} + h \\ &\sum_{t=1}^{n} \delta_t = 1 \\ &\delta_t \geq 1 \end{aligned} \tag{16}$$

3.3 Trade-Offs with Desirable and Undesirable Outputs

Assume that managers only focus on the agricultural system's output without considering explicit inputs (that is, inputs have been regarded as bottlenecks and cannot be reduced). We considered a nonmachine agricultural energy system to make effective trade-offs in need and undesired output. The procedure described below is the same as that designed by Mirzaei et al. [10].

Suppose there are $nDMU_j$: $j = 1, \dots, n$, with two good output vectors $y_{aj} = (y_{1aj}, \dots, y_{saj}) \geq 0$, $y_{bj} = (y_{1bj}, \dots, y_{sbj}) \geq 0$, and one bad output vector $z_j = (z_{1j}, \dots, z_{pj}) \geq 0$. By following Shepherd's [41] assumption, the following linear production technology can be used to solve bad (undesirable) output in the transportation system without the explicit inputs.

$$T_{\mathrm{WI}} = \left\{ (y_a, y_b, z) : \sum_{j=1}^{n} \delta_j y_{aj} \geq y_a, \sum_{j=1}^{n} \delta_j y_{bj} \geq y_b, \sum_{j=1}^{n} \delta_j z_j \geq z, \sum_{j=1}^{n} \delta_j = \theta, 0 \leq \theta \leq 1, \delta_j \geq 0, \forall j \right\}. \tag{17}$$

The following linear program using country "o" can be used.

$$\begin{aligned} &\min \ \theta^* \\ &\text{s.t.} \sum_{j=1}^{n} \delta_j y_{raj} \geq y_{rao}, \quad r = 1, \dots, s_a \\ &\sum_{j=1}^{n} \delta_j y_{rbj} \geq y_{rbo}, \quad r = 1, \dots, s_b \\ &\sum_{j=1}^{n} \delta_j z_{pj} \geq \theta^* z_{po}, \quad p = 1, \dots, P \\ &\sum_{j=1}^{n} \delta_j = \theta \\ &0 \leq \theta \leq 1, \ \delta_j \geq 0, \ j = 1, \dots, n. \end{aligned} \tag{18}$$

Consider that the bad output is from group N, and sound output belongs to group M. First, we have to choose a small number h (positive number) to solve the linear program problem at the second step.

$$\max \sum_{p\in M} d_p^1 z_p^+$$
$$\text{s.t.} \quad \sum_{j=1}^{n} \delta_j y_{raj} \geq y_{rao}, \quad r = 1, \ldots, s_a, \ \ r \nexists N$$
$$\sum_{j=1}^{n} \delta_j y_{raj} \geq y_{rao} + h, \quad r \exists N$$
$$\sum_{j=1}^{n} \delta_j y_{rbj} \geq y_{rbo}, \quad r = 1, \ldots, s_b, \ \ r \nexists N$$
$$\sum_{j=1}^{n} \delta_j y_{rbj} \geq y_{rbo} + h, \quad r \exists N \tag{19}$$
$$\sum_{j=1}^{n} \delta_j z_{pj} \geq \theta^* z_{po}, \quad p = 1, \ldots, P, \ \ p \nexists M$$
$$\sum_{j=1}^{n} \delta_j z_{pj} \geq z_p^+, \quad p \exists M$$
$$\sum_{j=1}^{n} \delta_j = \theta$$
$$0 \leq \theta \leq 1, \ \delta_j, z_p^+ \geq 0$$

$$\max \sum_{p\in M} d_p^1 z_p^+$$
$$\text{s.t.} \quad \sum_{j=1}^{n} \delta_j y_{raj} \geq y_{rao}, \quad r = 1, \ldots, s_a, \ \ r \nexists N$$
$$\sum_{j=1}^{n} \delta_j y_{raj} \geq y_{rao} + h, \quad r \exists N$$
$$\sum_{j=1}^{n} \delta_j y_{rbj} \geq y_{rbo}, \quad r = 1, \ldots, s_b, \ \ r \nexists N$$
$$\sum_{j=1}^{n} \delta_j y_{rbj} \geq y_{rbo} + h, \quad r \exists N \tag{20}$$
$$\sum_{j=1}^{n} \delta_j z_{pj} \geq \theta^* z_{po}, \quad p = 1, \ldots, P, \ \ p \nexists M$$
$$\sum_{j=1}^{n} \delta_j z_{pj} \geq z_p^+, \quad p \exists M$$
$$\sum_{j=1}^{n} \delta_j = \theta$$
$$0 \leq \theta \leq 1, \ \delta_j, z_p^+ \geq 0$$

We can calculate the positive and negative trade-off rate by simply replacing -*h* with *h* as shown below.

$$\tau_{pk}^{+}\left(y_{ao}, y_{bo}, z_o\right) = \frac{z_p^{+} - z_{po}}{h}$$
$$\tau_{pk}^{-}\left(y_{ao}, y_{bo}, z_o\right) = \frac{z_p^{-} - z_{po}}{h} \quad (21)$$
$$\forall p \exists M, k \exists N$$

3.4. Trade-Off Rates

It is assumed that there are objective conditions for basic trade-offs, so when the specific factor increases or even decreases by a small amount, it will determine the extreme change of the specific factor of the output vector. The below program enables us to solve the trade-offs

$$\max \quad z_{ko}^{'}$$
$$\text{s.t.} \quad z_o' \in T \quad (22)$$
$$\text{where } z_o^{'} = (z_{1o}, \ldots, z_{ko} + h, \ldots, z_{m+so})$$

Notice the new vector above even though it is output or input, and it is increasing function. The above model looks for an effective boundary on which to maximize or minimize a specific variable. However, in any case, the new point is the effective boundary, which is our requirement.

3.5. Illustrative Example

First, the SMB model is applied to the simple dataset in Table 1 of seven decision-making units (DMUs). Then, we show this in Table 2, with two inputs x_1 and x_2, and one output y_1, all DMUs are efficient. Mirzaei et al. have used this example with the help of the BCC model. It shows that DMU is useful, but there still exist slacks in the bad output. This makes DMUs weakly efficient, and we want to perform trade-offs which may reduce the bad output to help in getting the optimal efficiency level.

Table 1. The data set.

		Decision-Making Units (DMUs)						
		A	**B**	**C**	**D**	E	F	G
Inputs and out-	x_1	0.9	0.5	1.1	0.2	2.2	2.8	3
	x_2	1.63	1.36	1.55	2.15	2.04	1.40	2.04
	y_1	0.65	0.35	0.65	0.55	1.2	0.8	1.3

Table 2. The efficiency and the slacks.

DMU	x_1	x_2	y_1	ρ^*	s^-	s_g^+	s_b^-	**Ref**
A	0.9	1.63	0	1	0	0	1	A
B	0.5	1.36	0.35	1	0	0	1	A
C	1.1	1.55	0.65	1	0	0	0.7	A
D	0.2	2.15	0.55	1	0	0	0.4	A
E	2.2	2.04	1.2	1	0	0	0.8	A
F	2.8	1.40	0.8	1	0	0	0	G
G	3	2.04	1.3	1	0	0	0	G

Consider DMU$_A$ with $z_1: (-x_{11}, -x_{21}, y_1^*) = (-0.9, -1.63, 0.65)$. The change is needed to x_1 and x_2 when y_1 is changed by 1 unit (i.e., from 0.65 to 0.75). The optimistic method gives a new point on the frontier facet ACE (because in DMUA the four surfaces ABC, ABD, ADE, and ACE have a binding effect), where $(-x_{11}, -x_{21}, y_1^*) = (-1.136, -1.704, 0.75)$, where x_{11} indicates the first input of the first DMU (i.e., DMU A). The trade-offs rates $\tau_{13}^+ = 2.364$ and $\tau_{23}^+ = 0.745$ are the value change in the first and second input. This change occurs when a single output y_1 increases by 0.1 units. It is worth noting that $(-x_{11}, -x_{21}, y_1^*) = (-1.136, -1.704, 0.75)$ is the outcome of the following model:

$$
\begin{aligned}
&\min \quad z_1^* + z_2^* \\
&\text{s.t.} \quad -0.9\delta_1 - 0.5\delta_2 - 1.1\delta_3 - 0.2\delta_4 - 2.2\delta_5 - 2.8\delta_6 - 3\delta_7 \geq -z_1^* \\
&-1.63\delta_1 - 1.36\delta_2 - 1.55\delta_3 - 2.15\delta_4 - 2.04\delta_5 - 1.4\delta_6 - 2.04\delta_7 \geq -z_2^* \\
&0.65\delta_1 - 0.35\delta_2 - 0.65\delta_3 - 0.55\delta_4 - 1.2\delta_5 - 0.8\delta_6 - 1.3\delta_7 \geq 0.65 + 0.1 \\
&\delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 = 1 \\
&\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6, \delta_7 \geq 0
\end{aligned}
\tag{23}
$$

Let all points (i.e., ABC, ABD, and ADE) on the boundary to calculate a new trade-off rate. Changing in the direction would give a new point on a new efficiency frontier. For example, the points $(-x_{11}, -x_{21}, y_1^*) = (-0.815, -2.116, 0.75)$ are an efficient point of ADE, with trade-offs $\tau_{13}^- = -0.8462$ and $\tau_{23}^- = -4.8615$. In DMU_A, the two trade-off ratios, τ_{13}^+ and τ_{23}^+ indicate that if we increase y_1 from 0.65 to 0.75 (see Table 1), and changes are brought to the two inputs (i.e., changed to 1.1364 and 1.7045), DMU_A will still stay at the efficient boundary. While τ_{13}^- and τ_{23}^- mean that with *h* = +0.1, if both the inputs are changed to 0.8154 and 2.1162, respectively, it will remain on the effective boundary. Interestingly, in terms of two different efficient aspects, these two new points have a big difference in them. The point $(-x_{11}, -x_{21}, y_1^*) = (-0.815, -2.116, 0.75)$ is optimal because of the following program:

$$
\begin{aligned}
&\min \quad -z_1^* + z_2^* \\
&\text{s.t.} \quad -0.9\delta_1 - 0.5\delta_2 - 1.1\delta_3 - 0.2\delta_4 - 2.2\delta_5 - 2.8\delta_6 - 3\delta_7 \geq -z_1^* \\
&-1.63\delta_1 - 1.36\delta_2 - 1.55\delta_3 - 2.15\delta_4 - 2.04\delta_5 - 1.4\delta_6 - 2.04\delta_7 \geq -z_2^* \\
&0.65\delta_1 - 0.35\delta_2 - 0.65\delta_3 - 0.55\delta_4 - 1.2\delta_5 - 0.8\delta_6 - 1.3\delta_7 \geq 0.65 + 0.1 \\
&\delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 = 1 \\
&\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6, \delta_7 \geq 0
\end{aligned}
\tag{24}
$$

Two trade-offs τ_{13}^+, τ_{23}^+ and τ_{13}^-, τ_{23}^- are calculated (i.e., marginal rate of substitution to throughput N from group M) at an efficient point $z_o = -x_o, y_o$. The following three-step of Mirzaei et al. has been adapted:

1. Decide on the h. This should be a small number for k throughput.
2. Secondly, we solve the two linear program.

$$
\begin{gathered}
z_o^+ = \max \sum_{l \in M} d_l^{(1)} z_{lo}^* \\
\text{s.t.} \sum_{t=1}^{n} \delta_t z_{tl} \geq z_{lo}^*, \qquad l = 1.2 \ldots, m+s \\
\sum_{t=1}^{n} \delta_t = 1 \\
z_{lo}^* = z_{lo}, \quad l \nexists M, N \\
z_{ko}^* = z_{ko} + h, \quad l \in N \\
\delta_t, z_{lo}^* \geq 0, \quad \forall t, l
\end{gathered} \tag{25}
$$

$$
\begin{gathered}
z_o^- = \max \sum_{l \in M} d_l^{(2)} z_{lo}^* \\
\text{s.t.} \sum_{t=1}^{n} \delta_t z_{tl} \geq z_{lo}^*, \qquad l = 1.2 \ldots, m+s \\
\sum_{t=1}^{n} \delta_t = 1 \\
z_{lo}^* = z_{lo}, \quad l \nexists M, N \\
z_{ko}^* = z_{ko} + h, \quad l \in N \\
\delta_t, z_{lo}^* \geq 0, \quad \forall t, l
\end{gathered} \tag{26}
$$

Please note that $d_l^{(1)}$ and $d_l^{(2)}$ are the constant numbers, user-defined.

3. Calculate the trade-off of negative and positive rates from the right, as follows:

$$
\begin{gathered}
\tau_{jk}^+(z_o) = \frac{z_{jo}^+ - z_{jo}}{h} \\
\tau_{jk}^-(z_o) = \frac{z_{jo}^- - z_{jo}}{h} \\
\forall j \in M, k \in N.
\end{gathered} \tag{27}
$$

Trade-offs can be calculated by replacing -*h* with *h*. Because both the programs (26) and (25) make projections on the frontier points. Moreover, different trade-offs will result in other weighted vectors d. The weighted vector d is user-defined; it determines the efficient surface direction.

4. Analysis and Discussion

4.1. Efficiency Measuring Variables

Given developing countries, it can be observed from Akbar et al. (2020) [42,43] that the undesirable-outputs in any operations are not separable from the desirable-outputs, i.e., crop production and forest area. Reducing undesirable-output in practice inevitably leads to a reduction in desirable-output variables. Besides, certain undesirable-outputs can have significant effects (inseparable) on specific inputs. For example, emissions of methane and nitrous oxide gases (undesirable-outputs) in agricultural operations are proportional to the forest area and agricultural land area.

To illustrate the trade-offs, we selected the data consist of 136 countries. Here, the latest data set of the year 2019 is composed of multiple outputs and input variables, see Appendix A. For the trade-offs application, only the output variables are considered because the inputs are assumed to have reached the bottleneck in both ways that it cannot be increased or decreased by the managers. Among the four indicators, two are regarded as good-output variables, and two are the bad-output variables. The total crop production in each country is considered the first good-output y_1^g, and the forest area is the second desirable-output y_2^g. It is assumed that the more the forest area a DMU has, the less the area of crop production it utilizes. Not to mention that the crop production symbolizes the soil erosion and other operational activity causing emissions. The undesirable-outputs are methane emissions z_1^b and nitrous oxide emissions z_2^b purely from agricultural activity (considering the nonmachine agricultural operations), which positively correlates the two good-outputs. These indicators also relate to the ecological efficiency of agricultural operations, see Table 3.

Table 3. Variables for the agro-ecological efficiency.

	Variables	Unit of Measure	Source
Inputs			
x_1	Freshwater consumption	Billion cubic meters	World Bank
x_2	Agricultural land area	Percentage of land	World Bank
x_3	Fertilizer consumption	Percentage of fertilizer production	World Bank
x_4	Labor	Percentage of total employment	World Bank
Desirable Outputs			
y_1^g	Production	Crop production index	World Bank
y_2^g	Forest area	Percentage of land area	World Bank
Undesirable Output			
z_1^b	Methane emissions	Percentage of total emissions	World Bank
z_2^b	Nitrous oxide emissions	Percentage of total emissions	World Bank

4.2. Results and Discussion

The data set was evaluated for the countries' efficiencies using a program (12), and then we re-evaluated it using the model program (18). The data was taken as a whole without conversion for better analysis. The relative efficiency obtained using the model (12) is listed in Table 4. Countries with efficiency score 1 are fully efficient. We can see that 31 out of 136 countries have appeared efficient (i.e., when DMU = 1).

Suppose $M = \{1, 2\}$ and $N = \{1\}$. We wanted to calculate the effects of the marginal trade-off (i.e., change in the undesirable-outputs, methane emissions z_1^b and nitrous oxide emissions z_2^b), when applied to the first desirable-output "crop production y_1^g" and then second desirable-output "forest area y_2^g". It is important to note that for all effective countries, $h = 0.5$ and $h = -0.5$ proved to be feasible margins. This means that the increase or decrease within the marginal range (i.e., between 0.5 and −0.5) can further improve the macro efficiency due to the reduction in the excessive undesirable-outputs (indirect measures). Additionally, this is of course while maintaining other DMU's efficiency point on the frontier boundary, even if there is no improvement. In Appendix B, Table B1 and Table B2 show the trade-off effects (of all the 136 countries) on the methane (z_1^b) and nitrous oxide (z_2^b) when $h = +0.5$, -0.5 and $d = (1, 1)$. Here, within the text, only non-zero DMUs will be discussed, and DMUs with zero change are not mentioned (but they can be found in Appendix B).

Table 4. The efficiency results of 136 decision making units "DMUs" (countries).

DMUs	Eff.	DMUs	Eff.	DMUs	Eff.	DMUs	Eff.
Afghanistan	0.09	Estonia	1.00	Eritrea	0.18	Zimbabwe	0.23
Albania	0.25	Ethiopia	0.34	Namibia	0.13	Yemen	0.11
Algeria	1.00	Fiji	0.36	Nepal	0.24	Zambia	0.58
Angola	1.00	Finland	1.00	Netherlands	0.12	Vietnam	0.07
Antigua, Barbuda	1.00	France	0.16	Nicaragua	0.21	Ukraine	1.00
Argentina	1.00	Gabon	1.00	Niger	1.00	UAE	0.18
Armenia	0.20	Gambia	0.58	Nigeria	0.15	UK	0.12
Australia	0.20	Georgia	0.12	Norway	0.25	Uruguay	0.14
Austria	0.22	Germany	0.18	Oman	0.00	Uzbekistan	0.07
Azerbaijan	0.33	Ghana	0.45	Pakistan	0.02	Venezuela	0.16
Bahamas, The	1.00	Greece	0.14	Panama	0.38	Malta	0.08
Bangladesh	0.06	Guatemala	0.11	Papua New Guinea	1.00	Mauritius	0.10
Barbados	0.31	Guinea	0.39	Paraguay	0.24	Mexico	0.19
Belarus	0.17	Guyana	1.00	Philippines	0.13	Moldova	0.49
Belgium	0.21	Honduras	0.16	Poland	0.14	Mongolia	0.46
Belize	0.12	Hungary	0.15	Portugal	0.14	Morocco	0.16
Benin	0.91	Iceland	0.01	Romania	0.19	Dominica	1.00
Bhutan	1.00	Iran	0.15	Rwanda	0.51	Domin. Rep.	0.36
Bolivia	0.63	Iraq	0.11	Saudi Arabia	0.01	Ecuador	0.09
Bosnia, Herzegovina	0.17	Israel	0.22	Senegal	0.58	Egypt	0.00
Botswana	0.16	Italy	0.17	Slovak	0.30	Mozambique	1.00
Brunei Darussalam	1.00	Jamaica	0.27	Slovenia	0.19	El Salvador	0.09
Bulgaria	0.22	Japan	1.00	South Africa	0.18	Trinidad, Tobago	1.00
Burkina Faso	0.35	Jordan	0.07	Spain	0.17	Tunisia	0.24
Burundi	1.00	Kazakhstan	1.00	Sri Lanka	0.18	Turkey	0.13
Cambodia	1.00	Kenya	0.17	St. Kitts, Nevis	1.00	Uganda	0.11
Cameroon	1.00	Korea	0.16	St. Lucia	0.28	Madagascar	0.21
Central African	1.00	Kuwait	1.00	Suriname	1.00	Malawi	0.54
Chile	0.10	Kyrgyz	0.05	Sweden	1.00	Maldives	1.00
Congo, Dem.	1.00	Latvia	0.55	Switzerland	0.16	Mali	0.13
Congo, Rep.	1.00	Lebanon	0.06	Tajikistan	0.07	Cuba	0.13
Costa Rica	0.08	Lithuania	1.00	Tanzania	0.62	Cyprus	0.17
Cote d'Ivoire	0.38	Luxembourg	0.12	Thailand	0.14	Czech Republic	0.20
Croatia	0.23	Macedonia	0.31	Togo	0.18	Denmark	0.11

Now, to explain our experiments concisely, we shall go step by step discussing each bad output separately in order to identify the better trade-off point. Tables 5–8 show the results of the new value of undesirable outputs (z_1^b and z_2^b) when trade-off $h = \pm 0.5$ is applied separately on desirable-outputs y_1^g and y_2^g. The second columns in each resultant table show the trade-off value ($\tau^{\pm}$) with which trade-off takes place for each DMU.

Table 5. Trade-off effects on the methane (z_1^b) when *h* = +0.5 and d = (1, 1).

$\mathbf{DMU}_j$	w.r.t y_1^g z_1^{b+}	w.r.t y_1^g τ_{11}^+	w.r.t y_2^g z_1^{b+}	w.r.t y_2^g τ_{12}^+	$\mathbf{DMU}_j$	w.r.t y_1^g z_1^{b+}	w.r.t y_1^g τ_{11}^+	w.r.t y_2^g z_1^{b+}	w.r.t y_2^g τ_{12}^+
Afghanistan	11.4042	0.0071	11.3971	0.0000	Latvia	0.5898	0.0150	0.6966	0.1218
Albania	34.3414	0.1826	34.1588	0.0000	Lebanon	25.1189	−0.0018	25.1207	0.0000
Austria	45.9628	−0.0018	45.9669	0.0023	Luxem-bourg	30.2811	0.0367	30.2703	0.0259
Bangladesh	62.1303	0.0001	62.1302	0.0000	Macedonia	5.9849	0.0147	5.9781	0.0079
Belarus	43.2344	0.0124	43.1816	−0.0404	Madagascar	32.1777	−0.0019	32.1732	−0.0064
Belgium	43.6960	0.0587	43.6373	0.0000	Malawi	7.4308	0.0124	7.5967	0.1783
Belize	51.0052	0.0000	51.0072	0.0019	Mauritius	13.5227	−0.0022	13.5250	0.0000
Benin	14.3868	0.0667	14.5769	0.2568	Mongolia	6.3483	−0.5413	6.8895	0.0000
Bolivia	20.7527	−0.0007	20.7518	−0.0015	Namibia	1.3388	0.2113	1.1275	0.0000
Bosnia and Herze-govina	34.9513	0.0122	34.8993	−0.0397	Nepal	74.4329	−0.0029	74.4375	0.0018
Bulgaria	7.0032	−0.0009	7.0042	0.0000	Nicaragua	52.3281	0.0040	52.3819	0.0578
Chile	33.6971	−0.0011	33.6982	0.0000	Norway	7.1694	−0.0028	7.1756	0.0034
Costa Rica	61.9982	−0.0001	61.9984	0.0001	Oman	4.4126	−0.0003	4.4128	0.0000
Cote d'Iv-oire	12.0108	−0.0042	12.0177	0.0027	Pakistan	30.4262	−0.0306	30.4568	0.0000
Croatia	16.7472	−0.0008	16.7480	0.0000	Panama	19.0953	0.0933	18.8226	−0.1794
Cuba	5.5215	0.0240	5.5143	0.0169	Philippines	54.0918	−0.0010	54.0928	0.0000
Cyprus	40.0264	0.0000	40.0179	−0.0085	Poland	21.0054	−0.0013	21.0066	0.0000
Czech Rep.	28.4054	−0.0013	28.4067	0.0000	Portugal	26.1282	−0.0013	26.1295	0.0000
Ecuador	64.6114	−0.0010	64.6135	0.0012	Senegal	31.8184	0.0691	31.9967	0.2475
Egypt	26.8410	−0.0009	26.8419	0.0000	Slovak Rep.	21.7400	0.0160	21.6718	−0.0522
Eritrea	28.1564	0.0090	28.1474	0.0000	Slovenia	26.3791	0.0000	26.3819	0.0028
Fiji	52.9460	−0.0077	52.9780	0.0243	Sri Lanka	55.5878	−0.0005	55.5883	0.0000
Gambia, The	12.8958	0.0367	12.9796	0.1206	St. Lucia	31.6428	0.0247	31.5377	−0.0804
Georgia	40.2571	0.0000	40.2544	−0.0027	Switzerland	57.7132	−0.0027	57.7192	0.0033
Ghana	7.1747	0.0142	7.3637	0.2032	Thailand	52.6556	−0.0044	52.6708	0.0109
Greece	32.6785	0.0322	32.5415	−0.1048	Turkey	22.8057	−0.0011	22.8067	0.0000
Guatemala	47.2316	0.0007	47.2309	0.0000	Uganda	14.3203	0.0123	40.7055	26.3974
Guinea	18.7337	0.0029	18.7488	0.0180	UAE	5.3534	−0.0024	5.3531	−0.0028
Honduras	72.4080	−0.0004	72.4084	0.0000	Uzbekistan	19.9724	0.0006	19.9717	0.0000
Iceland	54.8233	0.0000	54.8234	0.0000	Venezuela	38.2000	−0.0013	38.2028	0.0016
Iran	17.4403	−0.0077	17.4480	0.0000	Vietnam	52.2606	−0.0003	52.2612	0.0003
Iraq	0.0000	0.0000	5.3387	5.3387	Zambia	35.7680	−0.0184	35.8049	0.0184
Jamaica	3.9368	−0.0025	3.9595	0.0202	Zimbabwe	35.3227	0.0079	35.3408	0.0259
Korea, Rep.	33.3108	−0.0007	33.3123	0.0008					

Now, if we analyze the results in Table 5 when h = +0.5 with d= (1, 1), 67 countries out of 136 showed the trade-off response for methane emission (z_1^b). Each good-output (y_1^gor y_2^g) is increased individually (one at a time) by 0.5 unit, the excessive bad-output is either increased, decreased, or remained the same. Let us examine three sample DMUs for understanding sake. Table 5 shows that if we increase y_1^g for Austria by 0.5 (i.e., from 89.48 to 89.98), see Table A1 in Appendix A, the methane emission (z_1^{b+}) is reduced to 45.9628 with the trade-off $\tau_{11}^+ = -0.0018$. However, when y_2^g is increased with $h = +0.5$ from 46.99 to 47.49, there is no change observed (i.e., $\tau_{12}^+ = 0$), which shows that there exists a lack of forest area. Similarly, when considering Pakistan, z_1^{b+} is seen with the reduction to 30.4262 with $\tau_{12}^{+} = -0.0306$ (when y_1^g is increased from 86.93 to 87.43, see Table A1, Appendix A), while there is no change when the trade-off is applied to y_2^g. In the case of Iraq, there is no change in methane emission z_1^{b+}, when crop production y_1^g is supposedly increased by $h = +0.5$, i.e., from 84.43 to 83.93 (showing the under-production), but there is an increase in z_1^{b+} with an increase in y_2^g indicating operational deficiencies i.e., massive soil erosion, etc. It is important to note that the DMUs with an increase in an undesirable-output have a minimal impact. It does not degrade the overall efficiency of those DMUs from their current efficiency point. This is due to the selection of feasible points ($h = +0.5, -0.5$). The good thing about this trade-off is that there are few DMUs (Bolivia, Madagascar, and UAE, etc.) which improve the efficiency with both undesirable outputs (y_1^g and y_2^g). It can easily be seen in Figure 1 that the trade-off in crop production (y_1^g) produces better efficiency mostly avoiding the extreme point as compared to the forest area (y_2^g).

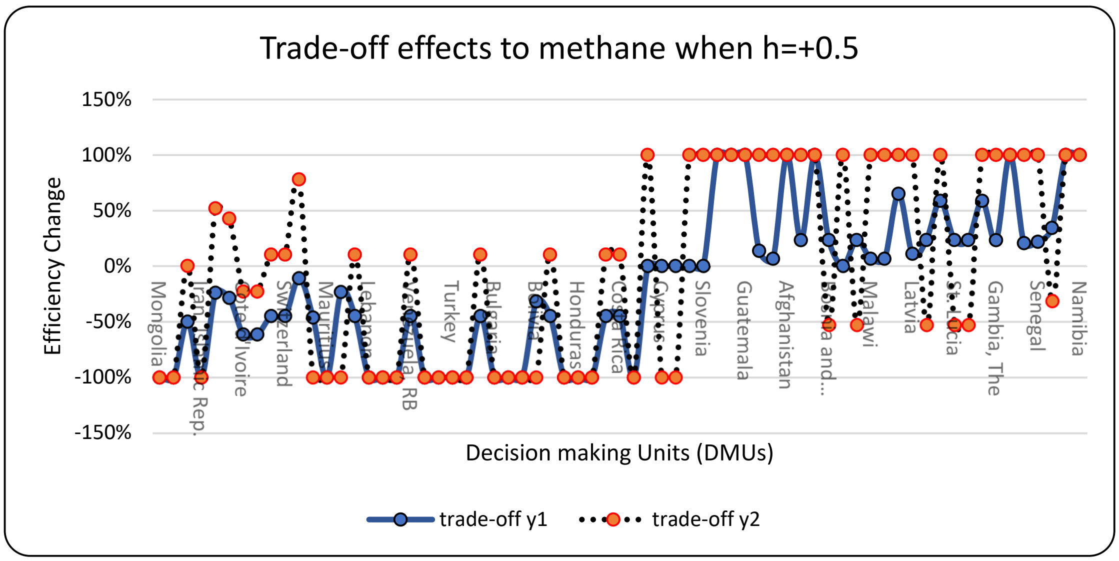

Figure 1. Trade-off effects on methane emissions (z_1^b), when $h = +0.5$.

Next, we look for the effects on methane emissions (z_1^b) in Table 6, when the trade-off is applied with $h = -0.5$ to y_1^g and y_2^g. Again, if we trade-off Austria's y_1^g with $h = -0.5$, i.e., from 49.48 to 48.98, the z_1^{b-} increases minimal with trade-off rate $\tau_{11}^{-} = 0.0018$, but it decreases as $z_1^{b-} = 45.9624$ with trade-off rate $\tau_{12}^{-} = -0.0023$ when y_2^g is reduced by $h = -0.5$ (from 46.99 to 46.49). Pakistan's situation does not fit this trade-off, as it increases or does not change with y_1^g and y_2^g, respectively. In Iraq's case, it does not make any difference with either reduction (crop production or forest area). Likewise, all the other DMUs can be checked in Table 6. With this trade-off (i.e., when $h = -0.5$), again we found that y_1^g produces a better result as compared to y_2^g (that is when the crop production is improved as compared to the improvement in the forest area), see Figure 2. It does not imply that the area of crop needs to be expanded. Of course, expending crop area will cause more agricultural erosion and maintenance, rather better production techniques for more production with the same crop area is the answer here.

Table 6. Trade-off effects on the methane (z_1^b) when h = −0.5 and d = (1, 1).

$\mathbf{DMU}_j$	w.r.t y_1^g		w.r.t y_2^g		$\mathbf{DMU}_j$	w.r.t y_1^g		w.r.t y_2^g	
	z_1^{b-}	τ_{11}^-	z_1^{b-}	τ_{12}^-		z_1^{b-}	τ_{11}^-	z_1^{b-}	τ_{12}^-
Afghanistan	11.3900	−0.0071	11.3971	0.0000	Luxembourg	30.2075	−0.0369	30.2180	−0.0264
Albania	33.9745	−0.1843	34.1588	0.0000	Macedonia	5.9554	−0.0148	5.9622	−0.0081
Austria	45.9665	0.0018	45.9624	−0.0023	Madagascar	32.1815	0.0019	32.1861	0.0065
Azerbaijan	0.0000	0.0000	0.0000	0.0000	Malawi	7.4059	−0.0125	7.2361	−0.1823
Bangladesh	62.1300	−0.0001	62.1302	0.0000	Maldives	0.0000	0.0000	0.0000	0.0000
Belarus	43.2096	−0.0124	43.2634	0.0414	Mauritius	13.5272	0.0023	13.5250	0.0000
Belgium	43.5784	−0.0589	43.6373	0.0000	Mongolia	7.4302	0.5406	6.8895	0.0000
Belize	51.0052	0.0000	51.0033	−0.0020	Namibia	0.9161	−0.2115	1.1275	0.0000
Benin	14.2538	−0.0664	14.0673	−0.2528	Nepal	74.4386	0.0029	74.4339	−0.0018
Bhutan	0.0000	0.0000	0.0000	0.0000	Netherlands	0.0000	0.0000	0.0000	0.0000
Bolivia	20.7541	0.0007	20.7549	0.0015	Nicaragua	52.3201	−0.0040	52.2650	−0.0591
Bosnia and Herzegovina	34.9269	−0.0122	34.9798	0.0407	Niger	0.0000	0.0000	0.0000	0.0000
Botswana	0.0000	0.0000	0.0000	0.0000	Norway	7.1749	0.0028	7.1687	−0.0035
Bulgaria	7.0051	0.0009	7.0042	0.0000	Oman	4.4131	0.0003	4.4128	0.0000
Chile	33.6993	0.0011	33.6982	0.0000	Pakistan	30.4875	0.0307	30.4568	0.0000
Costa Rica	61.9984	0.0001	61.9981	−0.0001	Panama	18.9085	−0.0935	19.1822	0.1802
Cote d'Ivoire	12.0193	0.0043	12.0124	−0.0027	Papua New Guinea	0.0000	0.0000	0.0000	0.0000
Croatia	16.7488	0.0008	16.7480	0.0000	Philippines	54.0938	0.0010	54.0928	0.0000
Cuba	5.4733	−0.0241	5.4802	−0.0173	Poland	21.0079	0.0013	21.0066	0.0000
Cyprus	40.0264	0.0000	40.0351	0.0087	Portugal	26.1308	0.0013	26.1295	0.0000
Czech Rep.	28.4080	0.0013	28.4067	0.0000	Saudi Arabia	0.0000	0.0000	5.3588	5.3588
Ecuador	64.6133	0.0010	64.6111	−0.0012	Senegal	31.6801	−0.0692	31.5000	−0.2492
Egypt	26.8428	0.0009	26.8419	0.0000	Slovak Rep.	21.7080	−0.0160	21.7774	0.0535
Eritrea	28.1384	−0.0090	28.1474	0.0000	Slovenia	26.3791	0.0000	26.3763	−0.0028
Fiji	52.9614	0.0077	52.9291	−0.0245	South Africa	0.0000	0.0000	0.0000	0.0000
Finland	0.0000	0.0000	0.0000	0.0000	Sri Lanka	55.5888	0.0005	55.5883	0.0000
Gambia, The	12.8221	−0.0369	12.7357	−0.1233	St. Lucia	31.5935	−0.0246	31.7005	0.0824
Georgia	40.2571	0.0000	40.2599	0.0028	Suriname	0.0000	0.0000	0.0000	0.0000
Germany	0.0000	0.0000	0.0000	0.0000	Switzerland	57.7186	0.0027	57.7125	−0.0034
Ghana	7.1463	−0.0142	6.9528	−0.2077	Tajikistan	0.0000	0.0000	0.0000	0.0000
Greece	32.6142	−0.0321	32.7537	0.1074	Thailand	52.6643	0.0044	52.6490	−0.0109
Guatemala	47.2302	−0.0007	47.2309	0.0000	Togo	0.0000	0.0000	0.0000	0.0000
Guinea	18.7279	−0.0029	18.7129	−0.0179	Turkey	22.8078	0.0011	22.8067	0.0000
Guyana	0.0000	0.0000	0.0000	0.0000	Uganda	14.2958	−0.0123	14.3081	0.0000
Honduras	72.4088	0.0004	72.4084	0.0000	Ukraine	0.0000	0.0000	0.0000	0.0000
Iceland	54.8234	0.0000	54.8234	0.0000	UAE	5.3583	0.0025	5.3589	0.0030
Iran	17.4558	0.0078	0.0000	−17.4480	UK	0.0000	0.0000	0.0000	0.0000
Israel	0.0000	0.0000	0.0000	0.0000	Uzbekistan	19.9711	−0.0006	0.0000	−19.9717

Jamaica	3.9417	0.0025	3.9190	−0.0203	Venezuela	38.2025	0.0013	38.1997	−0.0016
Japan	0.0000	0.0000	0.0000	0.0000	Vietnam	52.2611	0.0003	52.2606	−0.0003
Korea, Rep.	33.3122	0.0007	33.3106	−0.0009	Yemen, Rep.	0.0000	0.0000	0.0000	0.0000
Kuwait	0.0000	0.0000	0.0000	0.0000	Zambia	35.8049	0.0184	35.7679	−0.0186
Latvia	0.5596	−0.0151	0.4502	−0.1245	Zimbabwe	35.3069	−0.0079	35.2883	−0.0265
Lebanon	25.1225	0.0018	25.1207	0.0000					

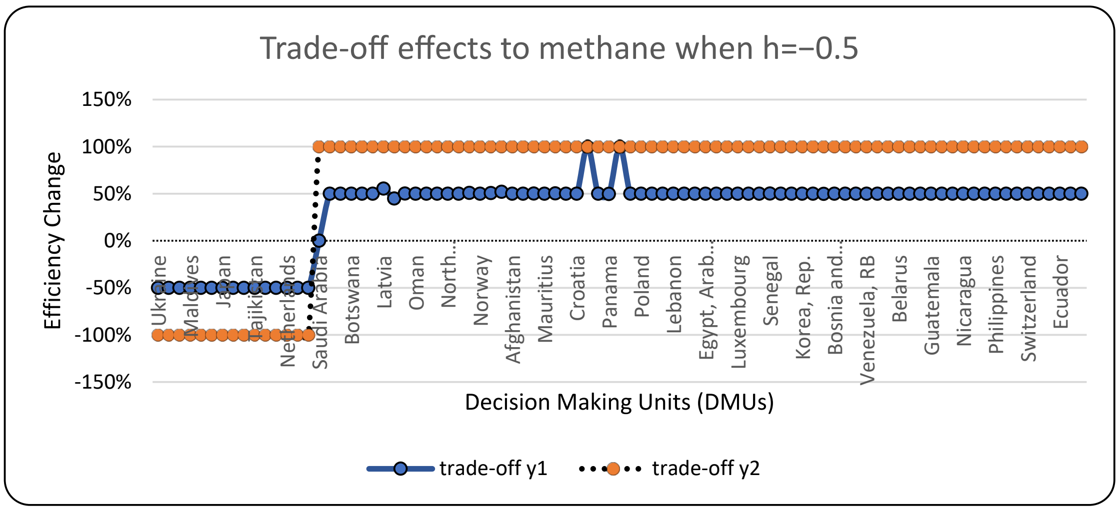

Figure 2. Trade-off effects on methane emissions (z_1^b), when $h = -0.5$.

Moving on to the second undesirable-output, the nitrous oxide z_2^b. We again performed the same experiment, when h= +0.5 with d= (1, 1), and the trade-off impact can be seen in Figure 3. However, quantitatively, Table 7 shows that if we increase desirable-output y_1^g for Austria by +0.5 (i.e., from 89.48 to 89.98), see Table A in Appendix A, the nitrous oxide emissions (z_2^{b+}) are not facing much rise i.e., 38.4120 with trade-off $\tau_{21}^+ = 0.0006$. However, when y_2^g is increased from 46.99 to 47.49 with $h = +0.5$, emissions are reduced to 38.3310 with $\tau_{22}^+ = -0.0804$, which shows that increasing the forest area would amply reduce the nitrous oxide emissions (z_2^{b+}). Similarly, when considering Pakistan, there is no effect at all on z_2^{b+} with either trade-off y_1^g or y_2^g (this is why the DMU "Pakistan" cannot be found in Table 7). In the case of Iraq, again there is no change in nitrous oxide emission z_2^{b+}, when crop production y_1^g is increased by $h = +0.5$, i.e., from 84.43 to 83.93 or when forest area y_2^g is increased from 1.91 to 2.41, see Table A in Appendix A. The overall efficiency is best seen when the trade-off is applied to y_1^g, it has rather a stable line as compared with y_2^g.

Table 7. Trade-off effects on the nitrous oxide (z_2^b) when h = +0.5 and d = (1, 1).

DMU_j	w.r.t y_1^g		w.r.t y_2^g		DMU_j	w.r.t y_1^g		w.r.t y_2^g	
	z_2^{b+}	τ_{21}^+	z_1^{b+}	τ_{22}^+		z_2^{b+}	τ_{21}^+	z_2^{b+}	τ_{22}^+
Albania	37.2237	0.1274	37.0963	0.0000	Jordan	44.6334	0.0005	44.6329	0.0000
Armenia	16.5679	0.0584	16.5095	0.0000	Korea	42.2038	0.0002	42.1734	−0.0302
Australia	49.3246	−0.0034	49.3280	0.0000	Latvia	34.2498	0.0686	34.4448	0.2636
Austria	38.4120	0.0006	38.3310	−0.0804	Lebanon	64.8009	−0.0405	64.8415	0.0000
Azerbaijan	11.0237	−0.0073	11.0310	0.0000	Luxembourg	1.1464	0.0145	1.2145	0.0826

Bangladesh	54.2884	0.0028	54.2856	0.0000	Macedonia	28.2280	0.0064	28.2486	0.0269
Barbados	8.4088	−0.0218	8.1748	−0.2558	Madagascar	40.0645	−0.0034	40.0531	−0.0148
Belarus	40.8051	0.0154	40.7027	−0.0871	Malawi	3.1914	0.0796	3.4974	0.3856
Belize	33.9164	0.0000	33.9593	0.0429	Malta	8.3159	0.0085	8.3075	0.0000
Bolivia	15.4115	0.0005	15.4105	−0.0004	Mauritius	38.7434	−0.0499	38.7932	0.0000
Bosnia and Herze-govina	62.5839	0.0151	62.4832	−0.0856	Mexico	27.9968	−0.0033	28.0264	0.0264
Botswana	46.6913	0.0157	46.6756	0.0000	Moldova	39.0884	−0.0090	39.0082	−0.0892
Bulgaria	31.6801	−0.0209	31.7010	0.0000	Nepal	43.0448	−0.0177	43.0762	0.0137
Chile	35.4870	−0.0252	35.5122	0.0000	Nether-lands	38.1764	−0.0090	38.1854	0.0000
Costa Rica	45.8674	0.0000	45.8621	−0.0053	Nicaragua	24.3967	0.0258	24.4959	0.1250
Cote d'Iv-oire	3.4436	−0.0260	3.4897	0.0201	Norway	41.9804	0.0009	41.8580	−0.1215
Croatia	26.9003	−0.0176	26.9179	0.0000	Oman	26.1590	−0.0063	26.1652	0.0000
Cuba	16.9863	0.0094	17.0308	0.0540	Paraguay	31.8761	0.0653	31.7728	−0.0381
Cyprus	42.0092	0.0000	41.8203	−0.1889	Philippines	56.6386	−0.0223	56.6609	0.0000
Czech Rep.	65.2515	−0.0284	65.2799	0.0000	Poland	34.4932	−0.0280	34.5212	0.0000
Denmark	58.9339	−0.0029	58.9369	0.0000	Portugal	38.1376	−0.0294	38.1670	0.0000
Dominican	18.4475	0.0403	18.4072	0.0000	Romania	5.6961	0.0154	5.7570	0.0763
Ecuador	54.8178	0.0003	54.7752	−0.0423	Rwanda	11.4551	0.0261	11.5463	0.1173
Egypt	41.6727	−0.0197	41.6924	0.0000	Saudi Ara-bia	18.3427	−0.0295	18.3722	0.0000
El Salvador	30.9759	-0.0044	30.9802	0.0000	Slovak Rep.	1.8577	0.0198	1.7255	−0.1124
Ethiopia	14.4607	−0.0664	24.8439	10.3167	Slovenia	35.5002	0.0000	35.5621	0.0619
Fiji	21.7064	0.0134	21.7505	0.0575	Spain	5.7476	−0.0139	5.8735	0.1120
France	39.4901	0.0007	39.4550	−0.0344	Sri Lanka	33.7308	−0.0115	33.7423	0.0000
Gambia, The	0.4388	0.0642	0.6542	0.2795	St. Lucia	1.7324	0.0306	1.5287	−0.1732
Georgia	25.5848	0.0000	25.5247	−0.0601	Switzerland	41.0546	0.0009	40.9359	−0.1179
Germany	10.6484	−0.0205	10.6761	0.0072	Thailand	38.9072	−0.0267	38.9528	0.0189
Ghana	4.8027	0.0907	5.1514	0.4394	Tunisia	8.8994	0.0388	8.8606	0.0000
Greece	41.5020	0.0399	41.2363	−0.2258	Turkey	48.6553	−0.0234	48.6787	0.0000
Guatemala	25.0176	0.0153	25.0023	0.0000	Uganda	0.0000	0.0000	61.1962	61.1962
Honduras	41.7701	−0.0093	41.7795	0.0000	UAE	27.0438	−0.0374	26.9642	−0.1170
Hungary	88.6208	−0.0309	88.6517	0.0000	UK	23.7600	−0.0133	23.7733	0.0000
Iceland	43.6784	−0.0018	43.6802	0.0000	Uzbekistan	59.7668	0.0144	59.7524	0.0000
Iran.	57.3186	−0.0441	57.3627	0.0000	Venezuela	39.7525	0.0004	39.6965	−0.0556
Israel	28.9126	−0.0198	28.9324	0.0000	Vietnam	52.7845	0.0001	52.7732	−0.0112
Italy	35.7060	0.0042	35.6679	−0.0339	Zimbabwe	27.0798	0.0138	27.1261	0.0601

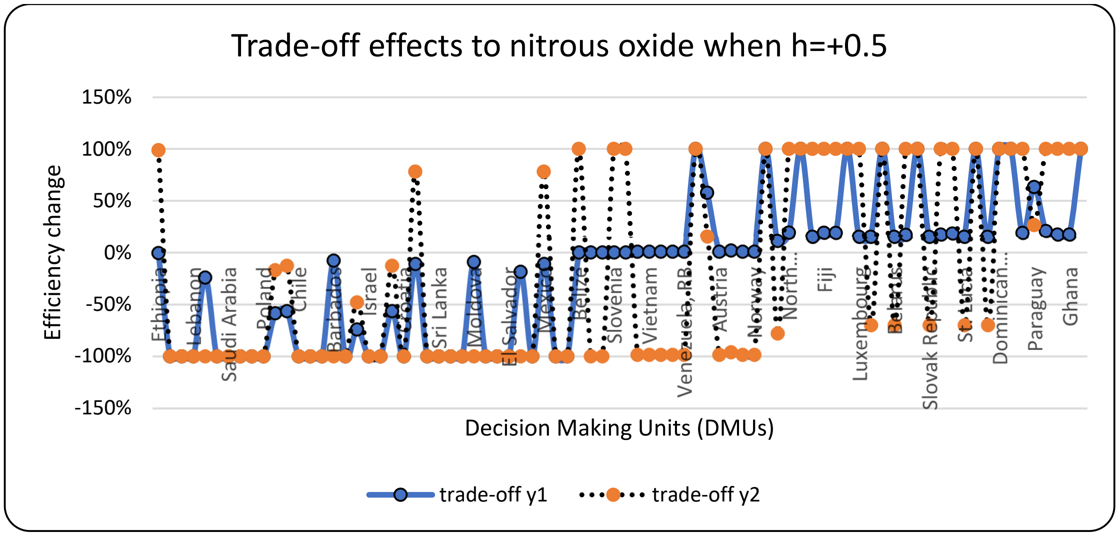

Figure 3. Trade-off effects on the nitrous oxide emissions (z_2^b), when $h = +0.5$.

Next, we look for the effects on nitrous oxide emissions (z_2^b) in Table 8, when the trade-off is applied to y_1^g and y_2^g with $h = -0.5$. Again, if we trade-off Austria's y_1^g with $h = -0.5$, i.e., from 49.48 to 48.98, the z_2^{b-} decreases to 38.4108 with trade-off rate $\tau_{21}^- = -0.0006$, but it increases as $z_1^{b-} = 38.4927$ with trade-off rate $\tau_{12}^- = 0.0812$ when y_2^g is reduced by $h = -0.5$ (from 46.99 to 46.49), see Table A in Appendix A. Again, Pakistan's situation does not show any improvement with the trade-off ($h = -0.5$) to y_1^g and y_2^g, respectively. In Iraq's case, it again does not make any difference with either reduction (such as crop production and forest area). However, in this trade-off experiment, we found some huge declines in nitrous oxide emissions, such as Iran ($\tau_{22}^- = -37.7437$) and Uzbekistan ($\tau_{22}^- = -43.0156$). Likewise, all the other DMUs can be checked in Table 8. Considering the overall DMUs efficiency (which collectively make a significant contribution to the world ecology), we again find that y_1^g produces a better result as compared to y_2^g (see Figure 4).

Table 8. Trade-off effects on the nitrous oxide (z_2^b) when $h = -0.5$ and $d = (1, 1)$.

DMU$_j$	w.r.t y_1^g		w.r.t y_2^g		DMU$_j$	w.r.t y_1^g		w.r.t y_2^g	
	z_2^{b-}	τ_{21}^-	z_2^{b-}	τ_{22}^-		z_2^{b-}	τ_{21}^-	z_2^{b-}	τ_{22}^-
Albania	36.9676	−0.1287	37.0963	0.0000	Korea, Rep.	42.2033	−0.0002	42.2340	0.0305
Armenia	16.4509	−0.0586	16.5095	0.0000	Latvia	34.1123	−0.0690	33.9119	−0.2694
Australia	49.3314	0.0034	49.3280	0.0000	Lebanon	64.8823	0.0408	64.8415	0.0000
Austria	38.4108	−0.0006	38.4927	0.0812	Luxembourg	1.1175	−0.0145	1.0476	−0.0844
Azerbaijan	11.0384	0.0073	11.0310	0.0000	North Macedonia	28.2153	−0.0064	28.1942	−0.0275
Bangladesh	54.2828	−0.0028	54.2856	0.0000	Madagascar	40.0712	0.0034	40.0829	0.0151
Barbados	8.4524	0.0219	8.7039	0.2734	Malawi	3.0319	−0.0799	2.7177	−0.3941
Belarus	40.7744	−0.0154	40.8790	0.0892	Malta	8.2990	−0.0085	8.3075	0.0000
Belize	33.9164	0.0000	33.8727	−0.0437	Mauritius	38.8434	0.0502	38.7932	0.0000
Benin	0.0000	0.0000	0.0000	0.0000	Mexico	28.0033	0.0033	27.9731	−0.0269
Bolivia	15.4104	−0.0005	15.4113	0.0004	Moldova	39.1064	0.0090	39.1879	0.0905

Bosnia and Herze-govina	62.5537	−0.0151	62.6565	0.0877	Mongolia	0.0000	0.0000	0.0000	0.0000
Botswana	46.6598	−0.0158	46.6756	0.0000	Namibia	0.0000	0.0000	0.0000	0.0000
Bulgaria	31.7221	0.0210	31.7010	0.0000	Nepal	43.0803	0.0178	43.0488	−0.0137
Chile	35.5376	0.0253	35.5122	0.0000	Nether-lands	38.1945	0.0091	38.1854	0.0000
Costa Rica	45.8673	0.0000	45.8726	0.0053	Nicaragua	24.3450	−0.0259	24.2431	−0.1278
Cote d'Iv-oire	3.4958	0.0262	3.4495	−0.0202	Norway	41.9786	−0.0009	42.1022	0.1227
Croatia	26.9355	0.0177	26.9179	0.0000	Oman	26.1715	0.0063	26.1652	0.0000
Cuba	16.9674	−0.0095	16.9217	−0.0552	Panama	0.0000	0.0000	0.0000	0.0000
Cyprus	42.0092	0.0000	42.2018	0.1926	Paraguay	31.7452	−0.0656	31.8491	0.0382
Czech Re-public	65.3085	0.0286	65.2799	0.0000	Philippines	56.6833	0.0225	56.6609	0.0000
Denmark	58.9398	0.0029	58.9369	0.0000	Poland	34.5494	0.0282	34.5212	0.0000
Dominican Republic	18.3667	−0.0405	18.4072	0.0000	Portugal	38.1966	0.0296	38.1670	0.0000
Ecuador	54.8172	−0.0003	54.8602	0.0427	Romania	5.6652	−0.0155	5.6028	−0.0780
Egypt	41.7122	0.0198	41.6924	0.0000	Rwanda	11.4028	−0.0262	11.3085	−0.1206
El Salvador	30.9846	0.0044	30.9802	0.0000	Saudi Ara-bia	18.4018	0.0296	29.9140	11.5419
Ethiopia	24.9627	10.4356	14.5271	0.0000	Senegal	0.0000	0.0000	0.0000	0.0000
Fiji	21.6796	−0.0134	21.6349	−0.0581	Slovak Rep.	1.8180	−0.0198	1.9530	0.1151
France	39.4887	−0.0007	39.5241	0.0347	Slovenia	35.5002	0.0000	35.4371	−0.0631
Gambia, The	0.3101	−0.0645	0.0887	−0.2859	Spain	5.7754	0.0139	5.6474	−0.1141
Georgia	25.5848	0.0000	25.6461	0.0613	Sri Lanka	33.7539	0.0116	33.7423	0.0000
Germany	10.6897	0.0208	10.6618	−0.0072	St. Lucia	1.6713	−0.0305	1.8793	0.1774
Ghana	4.6209	−0.0911	4.2629	−0.4492	Switzerland	41.0528	−0.0009	41.1728	0.1191
Greece	41.4223	−0.0398	41.6934	0.2313	Thailand	38.9607	0.0268	38.9149	−0.0190
Guatemala	24.9869	−0.0154	25.0023	0.0000	Tunisia	8.8217	−0.0389	8.8606	0.0000
Guinea	0.0000	0.0000	0.0000	0.0000	Turkey	48.7023	0.0235	48.6787	0.0000
Honduras	41.7889	0.0094	41.7795	0.0000	Uganda	0.0000	0.0000	0.0000	0.0000
Hungary	88.6828	0.0311	88.6517	0.0000	UAE	27.1187	0.0376	27.2035	0.1223
Iceland	43.6820	0.0018	43.6802	0.0000	UK	23.7867	0.0134	23.7733	0.0000
Iran	57.4069	0.0443	19.6190	−37.7437	Uzbekistan	59.7380	−0.0145	16.7369	−43.0156
Israel	28.9523	0.0199	28.9324	0.0000	Venezuela	39.7516	−0.0004	39.8082	0.0562
Italy	35.6976	−0.0042	35.7364	0.0346	Vietnam	52.7843	−0.0001	52.7957	0.0113
Jamaica	0.0000	0.0000	0.0000	0.0000	Zambia	0.0000	0.0000	0.0000	0.0000
Jordan	44.6324	−0.0005	44.6329	0.0000	Zimbabwe	27.0521	−0.0139	27.0044	−0.0615

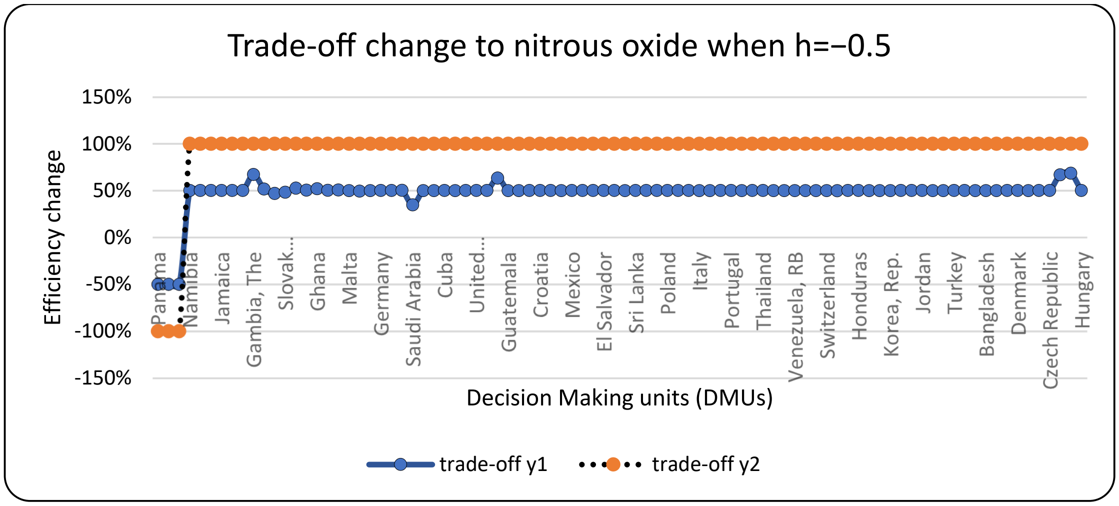

Figure 4. Trade-off effects on the nitrous oxide emissions (z_2^b), when $h = -0.5$.

Since we applied the same trade-off program with same trade-off margin (i.e., $h = \pm 0.5$) to each desirable-output (y_1^g and y_2^g) to see the efficient change in each undesirable-output (z_1^b and z_2^b), we established at each step that trade-off in y_1^g produced a better result in all four experiments above. Out of the four experiments, two experiments of trade-off $h = +0.5$ produced more efficient results among undesirable-outputs (z_1^b and z_2^b), see Figures 1 and 3. Now, if we compare it with the original emission values of methane z_1^b and nitrous oxide z_2^b, we can authenticate that trade-off point at $h = +0.5$ is the optimal trade-off point to achieve indirect efficiency, see Figure 5. There is an improvement in almost all the inefficient countries except those with zero change (Algeria, Angola, and Argentina, etc.). There are no deficiencies to the unchanged DMUs, either they were already at the efficient frontier or below the frontier line. Figure 5 shows the change in emissions in both the methane and the nitrous oxide with trade-off $h = 0$ to $h = +0.5$. Resultantly, we found that trade-off in the better crop production quantity makes the maximum result out of it. The marginal trade-off is found to be the best and fastest policy action for the majority of the ecological deficiency solutions.

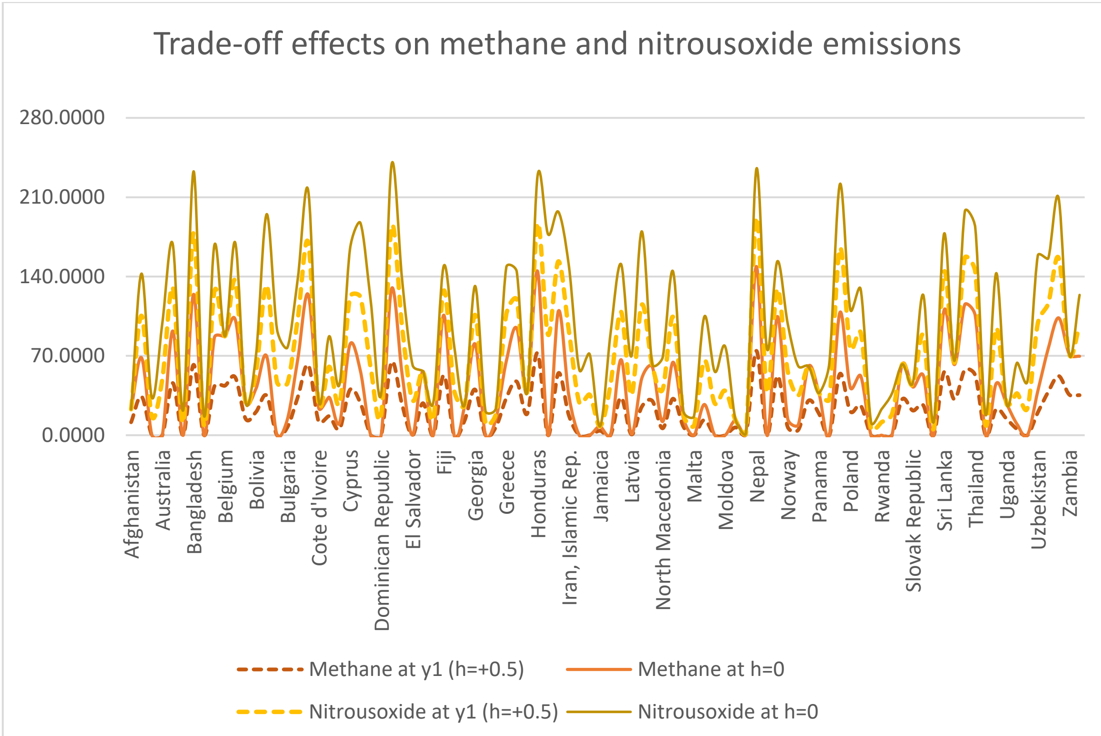

Figure 5. The efficiency change with trade-off $h = +0.5$ values with desirable outputs (y_1^{g+}).

5. Conclusions

Agriculture is becoming the center of concern in terms of food security and ecological betterment. This paper produces unique trade-off methodology unlike the existing trade-offs which uses theoretical logic and hypotheses to hypothesize the maximum change, i.e., when we change one variable, other performance variables will have an impact. However, we used the practical example to the marginal trade-off in the agricultural ecological context.

The DEA weighted slack based measurement was used to analyze the trade-off behavior between undesirable-output variables in terms of efficiencies. We obtained different results from several experiments and found the best efficiency point out of each experiment. It was found that it is possible to get different trade-off margins for each experiment. In our case, 136 developing countries were evaluated for their agro-ecological efficiency, where 31 countries were found efficient. The inefficient countries were further examined with the trade-off model by selecting the marginal range of $h = \pm 0.5$. The interesting point is that all the values between this margin produced almost the same result. The obtained results prove that the trade-off of $h = +0.5$, in good-output (i.e., crop production y_1^g) produces efficient results, which means that it not only increases the good-output (which is desirable), but also reduces the undesirable emissions (i.e., methane emission z_1^b and nitrous oxide emissions z_2^b). This implies that the improved crop production (without increasing the agricultural land area) with effective managerial technique can help in reaching the efficiency frontier boundary. Therefore, we suggest that adopting the crop efficient production technique can yield the best ecological results and also improve the agricultural economic viability.

The results obtained using real numerical data prove this method's applicability in different agricultural energy efficiency assessments and improvements. This can be very helpful for the policy designers and the decision makers, who are responsible for the resource consumption and production at both the micro and macro level operations. However, this study is made limited to output variables (i.e., two good and two bad variables), which is different from the previous studies. The number of variables adopted in this study is subject to the data availability, therefore indicates the study limitations. Future research can be expanded by considering more output variables or more comprehensive data (including input variables, for example), such as applying marginal trade-offs to more input variables and examining the behavior of alternate output variables to find better results. Moreover, the application research in the conditional DEA method needs to be explored further.

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Data Availability Statement: All the variables and related data is collected from the World Bank (https://data.worldbank.org/). The countries with missing data was eliminated for better results and finally 136 countries were included in the analysis. The section 4.1 further details the variable collected.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

The dataset of 136 developing countries. The dataset shows the four inputs namely freshwater consumption (x_1), agricultural land area (x_2), fertilizer consumption (x_3), and total agricultural labor (x_4). Additionally, the four outputs are composed of two desirable-outputs namely production (y_1^g) and forest area (y_2^g), whereas, the two undesirable-outputs are methane emissions (z_1^b) and nitrous oxide emissions (z_2^b).

Table A1. Developing countries.

Country	x_1	x_2	x_3	x_4	y_1^g	y_2^g	z_1^b	z_2^b
Afghanistan	47.20	58.13	12.20	42.84	160.98	2.07	65.51	68.93
Albania	26.90	44.56	126.10	36.69	211.23	28.15	83.01	97.37
Algeria	11.30	17.64	22.30	9.86	202.71	0.92	8.05	49.48
Angola	148.00	48.02	8.00	50.38	283.95	46.02	15.05	78.09
Antigua and Barbuda	0.10	20.45	13.90	0.01	110.76	22.16	65.79	48.81
Argentina	292.00	57.89	50.30	0.09	149.88	9.49	66.01	99.85
Armenia	6.90	64.60	110.50	29.64	173.67	11.64	21.57	92.19
Australia	492.00	47.35	68.10	2.56	115.68	15.91	52.26	93.26
Austria	55.00	31.95	141.80	3.58	89.48	46.99	46.41	66.86
Azerbaijan	8.10	57.81	14.10	35.87	129.60	14.92	35.07	81.19
Bahamas, The	0.70	1.47	144.00	2.14	162.44	51.45	1.39	30.85
Bangladesh	105.00	69.56	289.40	38.58	167.26	10.90	63.56	86.05
Barbados	0.10	23.67	113.80	2.63	47.83	14.65	18.32	32.92
Belarus	34.00	41.95	146.60	11.02	114.46	43.01	48.38	71.53
Belgium	12.00	43.38	318.50	0.96	94.78	22.75	74.20	30.75
Belize	15.30	7.16	466.20	16.85	100.19	58.88	52.59	69.22
Benin	10.30	33.91	14.70	38.58	169.68	36.65	49.25	74.39
Bhutan	78.00	13.49	13.30	55.31	118.40	74.53	30.03	38.69
Bolivia	303.50	35.12	7.60	30.71	166.59	49.10	39.90	83.99

Bosnia and Herzegovina	35.50	42.55	131.80	15.38	107.60	42.68	41.18	94.47
Botswana	2.40	45.76	89.60	20.69	130.65	18.38	75.41	#####
Brunei Darussalam	8.50	3.04	141.80	1.36	97.74	70.90	0.14	43.09
Bulgaria	21.00	44.94	125.50	6.39	126.55	36.43	8.08	55.74
Burkina Faso	12.50	46.98	21.80	25.23	159.82	18.77	78.81	85.75
Burundi	10.10	80.18	5.40	92.02	105.27	12.55	14.61	54.39
Cambodia	120.60	32.03	17.40	32.30	286.48	50.86	69.18	25.64
Cameroon	273.00	21.20	9.70	43.44	219.29	38.15	59.82	87.96
Central African Republic	141.00	8.09	0.30	77.32	123.05	35.49	74.04	91.89
Chile	885.00	21.35	293.80	9.00	119.23	24.18	34.72	58.16
Congo, Dem. Rep.	900.00	11.66	2.50	65.43	113.18	66.76	21.81	45.92
Congo, Rep.	222.00	31.19	1.80	34.13	138.20	65.24	19.43	74.21
Costa Rica	113.00	34.68	604.90	12.11	141.52	56.01	63.01	79.62
Cote d'Ivoire	76.80	66.28	51.70	40.05	135.19	32.76	16.58	30.39
Croatia	37.70	29.23	119.30	5.96	132.29	34.57	17.88	52.04
Cuba	38.10	59.33	49.40	17.51	79.02	33.04	58.80	72.12
Cyprus	0.80	10.87	196.70	2.07	52.64	18.72	40.53	53.24
Czech Republic	13.20	44.99	196.10	2.72	113.72	34.65	29.38	86.88
Denmark	6.00	62.07	131.10	2.19	111.04	14.85	59.01	#####
Dominica	0.20	35.41	88.10	0.01	117.44	56.44	58.32	47.09
Dominican Republic	23.50	47.78	88.10	9.02	177.43	44.39	53.24	74.37
Ecuador	442.40	23.86	345.40	29.20	123.31	49.33	65.49	84.55
Egypt, Arab Rep.	1.80	3.90	649.20	23.79	128.62	0.08	27.94	66.12
El Salvador	15.60	76.08	132.40	16.28	115.13	12.06	50.74	74.16
Eritrea	2.80	75.47	2.80	61.21	81.25	14.78	66.98	83.04
Estonia	12.70	24.85	112.70	3.18	197.25	51.16	19.65	70.36
Ethiopia	122.00	38.85	14.40	66.13	232.09	12.00	65.84	87.96
Fiji	28.60	23.19	46.00	36.26	67.64	55.84	79.11	89.39
Finland	107.00	7.55	80.50	3.61	95.19	73.09	15.27	35.38
France	200.00	51.87	163.10	2.44	96.06	31.92	41.70	81.26
Gabon	164.00	20.03	26.80	32.83	135.50	89.45	3.17	16.28
Gambia, The	3.00	65.04	1.20	27.12	107.13	48.98	53.49	85.37
Georgia	58.10	32.25	170.80	41.82	69.55	41.03	41.36	50.19
Germany	107.00	47.45	197.20	1.21	103.59	32.79	54.16	55.19
Ghana	30.30	71.16	20.90	29.26	175.83	41.55	36.14	95.20
Greece	58.00	46.46	123.00	11.98	85.03	32.47	36.80	65.00
Guatemala	109.20	32.28	303.20	31.49	188.64	31.51	48.84	60.83
Guinea	226.00	60.19	1.60	61.74	147.09	25.35	47.48	61.37
Guyana	241.00	8.51	44.60	17.14	131.40	83.85	72.14	87.35
Honduras	90.70	29.65	164.30	30.26	146.42	37.68	73.66	69.59
Hungary	6.00	55.52	128.30	4.70	89.28	23.30	24.76	#####
Iceland	170.00	18.61	181.50	3.94	96.94	0.57	54.97	86.42
Iran, Islamic Rep.	128.50	24.23	76.30	17.95	111.13	6.78	19.29	80.02
Iraq	35.20	20.76	35.80	18.10	84.43	1.91	14.37	33.34
Israel	0.80	23.93	280.70	0.92	103.31	7.65	32.11	62.06
Italy	182.50	42.56	129.80	3.68	88.87	32.50	35.33	78.07
Jamaica	10.80	39.63	57.20	15.93	102.44	30.81	48.02	44.59
Japan	430.00	12.07	242.20	3.42	85.30	68.54	74.62	30.71
Jordan	0.70	11.88	112.00	3.08	151.59	1.09	16.85	80.20
Kazakhstan	64.40	80.89	4.30	15.80	166.32	1.22	18.35	#####
Kenya	20.70	49.17	38.20	54.44	151.83	8.19	51.52	88.58

Korea, Rep.	64.90	17.08	380.30	4.88	90.96	63.04	33.50	80.50
Kuwait	0.00	8.52	750.70	2.01	245.80	0.38	1.54	23.55
Kyrgyz Republic	48.90	54.54	31.40	21.17	114.91	2.92	68.18	86.83
Latvia	16.90	32.50	104.20	6.75	181.48	54.67	15.05	95.64
Lebanon	4.80	65.88	330.90	13.61	92.86	13.58	25.91	82.48
Lithuania	15.50	47.32	131.90	6.87	204.60	35.63	23.12	34.02
Luxembourg	1.00	54.56	262.10	1.01	77.08	35.68	83.51	58.98
North Macedonia	5.40	47.30	79.30	15.38	131.41	40.40	37.23	70.64
Madagascar	337.00	71.70	5.20	64.22	136.70	21.11	63.35	#####
Malawi	16.10	65.97	21.60	43.65	199.30	32.13	32.19	88.20
Maldives	0.00	22.12	314.90	8.47	54.67	3.33	0.60	24.95
Mali	60.00	34.41	44.20	62.59	197.21	3.64	78.13	77.10
Malta	0.10	32.43	264.60	0.99	102.31	1.09	16.76	54.44
Mauritius	2.80	39.98	235.30	6.07	76.87	18.65	14.18	53.39
Mexico	409.00	54.88	114.00	12.61	131.19	33.72	46.86	73.72
Moldova	1.60	73.65	24.40	35.93	99.97	13.23	16.11	72.61
Mongolia	34.80	70.00	40.00	27.42	362.87	8.61	94.48	#####
Morocco	29.00	68.31	71.10	34.69	143.03	13.18	46.85	76.83
Mozambique	100.30	64.35	3.70	70.33	185.40	47.19	27.30	26.38
Namibia	6.20	47.13	26.10	22.13	128.33	8.08	90.25	97.74
Nepal	198.20	28.37	74.10	65.00	155.00	24.94	79.99	76.31
Netherlands	11.00	53.16	288.90	2.04	112.46	11.33	43.86	77.92
Nicaragua	156.20	41.27	61.50	30.65	143.10	23.93	70.58	86.48
Niger	3.50	38.80	0.40	75.06	266.68	0.87	40.66	71.34
Nigeria	221.00	77.52	5.50	35.10	122.32	6.57	33.25	90.05
Norway	382.00	2.64	203.90	2.06	90.60	33.17	7.87	61.94
Oman	1.40	4.80	468.10	4.56	151.71	0.01	5.71	54.98
Pakistan	55.00	46.63	144.30	36.66	125.41	1.74	57.11	78.92
Panama	136.60	30.51	49.10	13.95	86.93	61.24	74.97	76.40
Papua New Guinea	801.00	2.87	112.10	58.32	133.13	74.08	12.09	27.33
Paraguay	117.00	57.43	110.30	20.13	198.41	36.32	82.74	#####
Philippines	479.00	43.67	157.40	23.41	124.13	26.78	55.15	80.24
Poland	53.60	44.05	172.80	9.23	114.37	31.17	21.98	56.24
Portugal	38.00	38.98	199.40	5.85	112.00	34.26	27.09	59.44
Romania	42.40	58.10	59.90	21.71	97.25	30.21	30.76	63.40
Rwanda	9.50	73.98	10.90	62.41	185.02	21.63	32.50	83.92
Saudi Arabia	2.40	80.64	176.90	2.40	72.52	0.45	5.98	43.69
Senegal	25.80	47.26	16.40	30.05	176.82	42.15	63.84	87.55
Slovak Republic	12.60	37.07	125.80	2.18	99.43	40.48	28.14	32.72
Slovenia	18.70	34.12	258.90	5.23	83.12	62.18	28.05	72.78
South Africa	44.80	79.36	58.50	5.09	118.09	7.62	24.91	71.23
Spain	111.20	51.00	144.00	4.09	106.51	38.04	58.83	65.86
Sri Lanka	52.80	46.50	131.90	24.52	142.66	32.59	56.81	60.84
St. Kitts and Nevis	0.00	19.78	0.50	0.00	14.94	42.31	23.39	52.95
St. Lucia	0.30	15.97	170.90	17.27	38.59	32.90	44.75	36.60
Suriname	99.00	0.55	217.70	7.52	185.11	98.18	67.90	#####
Sweden	171.00	7.33	96.30	1.65	116.40	68.87	24.66	61.85
Switzerland	40.40	38.13	214.40	2.95	97.97	32.15	58.53	60.35
Tajikistan	63.50	34.67	81.40	44.92	181.47	2.96	60.35	92.60
Tanzania	84.00	47.43	12.60	65.31	221.61	50.35	57.99	88.34
Thailand	224.50	45.17	161.70	31.61	133.65	31.84	54.85	66.14

Togo	11.50	73.03	11.00	37.70	152.45	2.76	28.09	66.29
Trinidad and Tobago	3.80	10.07	356.00	2.97	46.37	45.25	0.26	86.63
Tunisia	4.20	65.45	59.30	13.03	135.06	7.14	22.24	79.08
Turkey	227.00	48.36	137.70	18.38	122.29	15.82	23.85	71.90
Uganda	39.00	75.72	1.90	72.67	75.50	8.88	56.66	91.70
Ukraine	55.10	71.60	52.70	14.48	200.85	16.68	13.03	33.77
United Arab Emirates	0.20	4.52	714.90	1.41	45.19	4.59	5.67	32.76
United Kingdom	145.00	71.81	252.90	1.03	103.43	13.17	46.45	63.12
Uruguay	92.20	81.24	143.70	8.12	232.20	11.58	92.76	94.71
Uzbekistan	16.30	62.57	232.70	23.92	187.10	7.59	21.57	95.29
Venezuela, RB	805.00	24.50	183.50	8.31	98.62	52.39	38.68	71.47
Vietnam	359.40	40.77	429.80	37.36	151.68	51.00	53.50	83.41
Yemen, Rep.	2.10	44.53	16.40	28.98	142.45	1.04	35.29	64.11
Zambia	80.20	32.70	89.60	48.84	237.04	64.56	48.98	63.47
Zimbabwe	12.30	42.78	22.90	66.54	96.18	33.64	66.63	91.40

Appendix B

Table A2. Trade-off effects on the methane (z_1^b) and nitrous oxide (z_2^b) when h = +0.5 and d = (1, 1).

DMU_j	Methane Emissions z_1^b				Nitrous Oxide Emissions z_2^b			
	w.r.t y_1		w.r.t y_2		w.r.t y_1		w.r.t y_2	
	z_1^{b+}	τ_{11}^+	z_1^{b+}	τ_{12}^+	z_2^{b+}	τ_{21}^+	z_2^{b+}	τ_{22}^+
Afghanistan	11.4042	0.0071	11.3971	0.0000	0.0000	0.0000	0.0000	0.0000
Albania	34.3414	0.1826	34.1588	0.0000	37.2237	0.1274	37.0963	0.0000
Algeria	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Angola	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Antigua/Barbuda	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Argentina	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Armenia	0.0000	0.0000	0.0000	0.0000	16.5679	0.0584	16.5095	0.0000
Australia	0.0000	0.0000	0.0000	0.0000	49.3246	−0.0034	49.3280	0.0000
Austria	45.9628	−0.0018	45.9669	0.0023	38.4120	0.0006	38.3310	−0.0804
Azerbaijan	0.0000	0.0000	0.0000	0.0000	11.0237	−0.0073	11.0310	0.0000
Bahamas	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bangladesh	62.1303	0.0001	62.1302	0.0000	54.2884	0.0028	54.2856	0.0000
Barbados	0.0000	0.0000	0.0000	0.0000	8.4088	−0.0218	8.1748	−0.2558
Belarus	43.2344	0.0124	43.1816	−0.0404	40.8051	0.0154	40.7027	−0.0871
Belgium	43.6960	0.0587	43.6373	0.0000	0.0000	0.0000	0.0000	0.0000
Belize	51.0052	0.0000	51.0072	0.0019	33.9164	0.0000	33.9593	0.0429
Benin	14.3868	0.0667	14.5769	0.2568	0.0000	0.0000	0.0000	0.0000
Bhutan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bolivia	20.7527	−0.0007	20.7518	−0.0015	15.4115	0.0005	15.4105	−0.0004
Bosnia/Herzegovina	34.9513	0.0122	34.8993	−0.0397	62.5839	0.0151	62.4832	−0.0856
Botswana	0.0000	0.0000	0.0000	0.0000	46.6913	0.0157	46.6756	0.0000
Brunei Darussalam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bulgaria	7.0032	−0.0009	7.0042	0.0000	31.6801	−0.0209	31.7010	0.0000
Burkina Faso	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Burundi	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cambodia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Cameroon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Central African	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Chile	33.6971	−0.0011	33.6982	0.0000	35.4870	−0.0252	35.5122	0.0000
Congo, Dem. Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Congo, Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Costa Rica	61.9982	−0.0001	61.9984	0.0001	45.8674	0.0000	45.8621	−0.0053
Cote d'Ivoire	12.0108	−0.0042	12.0177	0.0027	3.4436	−0.0260	3.4897	0.0201
Croatia	16.7472	−0.0008	16.7480	0.0000	26.9003	−0.0176	26.9179	0.0000
Cuba	5.5215	0.0240	5.5143	0.0169	16.9863	0.0094	17.0308	0.0540
Cyprus	40.0264	0.0000	40.0179	−0.0085	42.0092	0.0000	41.8203	−0.1889
Czech Republic	28.4054	−0.0013	28.4067	0.0000	65.2515	−0.0284	65.2799	0.0000
Denmark	0.0000	0.0000	0.0000	0.0000	58.9339	−0.0029	58.9369	0.0000
Dominica	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Dominican Rep.	0.0000	0.0000	0.0000	0.0000	18.4475	0.0403	18.4072	0.0000
Ecuador	64.6114	−0.0010	64.6135	0.0012	54.8178	0.0003	54.7752	−0.0423
Egypt, Arab Rep.	26.8410	−0.0009	26.8419	0.0000	41.6727	−0.0197	41.6924	0.0000
El Salvador	0.0000	0.0000	0.0000	0.0000	30.9759	−0.0044	30.9802	0.0000
Eritrea	28.1564	0.0090	28.1474	0.0000	0.0000	0.0000	0.0000	0.0000
Estonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethiopia	0.0000	0.0000	0.0000	0.0000	14.4607	−0.0664	24.8439	10.3167
Fiji	52.9460	−0.0077	52.9780	0.0243	21.7064	0.0134	21.7505	0.0575
Finland	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
France	0.0000	0.0000	0.0000	0.0000	39.4901	0.0007	39.4550	−0.0344
Gabon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gambia, The	12.8958	0.0367	12.9796	0.1206	0.4388	0.0642	0.6542	0.2795
Georgia	40.2571	0.0000	40.2544	−0.0027	25.5848	0.0000	25.5247	−0.0601
Germany	0.0000	0.0000	0.0000	0.0000	10.6484	−0.0205	10.6761	0.0072
Ghana	7.1747	0.0142	7.3637	0.2032	4.8027	0.0907	5.1514	0.4394
Greece	32.6785	0.0322	32.5415	−0.1048	41.5020	0.0399	41.2363	−0.2258
Guatemala	47.2316	0.0007	47.2309	0.0000	25.0176	0.0153	25.0023	0.0000
Guinea	18.7337	0.0029	18.7488	0.0180	0.0000	0.0000	0.0000	0.0000
Guyana	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Honduras	72.4080	−0.0004	72.4084	0.0000	41.7701	−0.0093	41.7795	0.0000
Hungary	0.0000	0.0000	0.0000	0.0000	88.6208	−0.0309	88.6517	0.0000
Iceland	54.8233	0.0000	54.8234	0.0000	43.6784	−0.0018	43.6802	0.0000
Iran, Islamic Rep.	17.4403	−0.0077	17.4480	0.0000	57.3186	−0.0441	57.3627	0.0000
Iraq	0.0000	0.0000	5.3387	5.3387	0.0000	0.0000	0.0000	0.0000
Israel	0.0000	0.0000	0.0000	0.0000	28.9126	−0.0198	28.9324	0.0000
Italy	0.0000	0.0000	0.0000	0.0000	35.7060	0.0042	35.6679	−0.0339
Jamaica	3.9368	−0.0025	3.9595	0.0202	0.0000	0.0000	0.0000	0.0000
Japan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Jordan	0.0000	0.0000	0.0000	0.0000	44.6334	0.0005	44.6329	0.0000
Kazakhstan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kenya	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Korea, Rep.	33.3108	−0.0007	33.3123	0.0008	42.2038	0.0002	42.1734	−0.0302
Kuwait	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kyrgyz Republic	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Latvia	0.5898	0.0150	0.6966	0.1218	34.2498	0.0686	34.4448	0.2636
Lebanon	25.1189	−0.0018	25.1207	0.0000	64.8009	−0.0405	64.8415	0.0000
Lithuania	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Luxembourg	30.2811	0.0367	30.2703	0.0259	1.1464	0.0145	1.2145	0.0826

North Macedonia	5.9849	0.0147	5.9781	0.0079	28.2280	0.0064	28.2486	0.0269
Madagascar	32.1777	−0.0019	32.1732	−0.0064	40.0645	−0.0034	40.0531	−0.0148
Malawi	7.4308	0.0124	7.5967	0.1783	3.1914	0.0796	3.4974	0.3856
Maldives	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mali	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Malta	0.0000	0.0000	0.0000	0.0000	8.3159	0.0085	8.3075	0.0000
Mauritius	13.5227	−0.0022	13.5250	0.0000	38.7434	−0.0499	38.7932	0.0000
Mexico	0.0000	0.0000	0.0000	0.0000	27.9968	−0.0033	28.0264	0.0264
Moldova	0.0000	0.0000	0.0000	0.0000	39.0884	−0.0090	39.0082	−0.0892
Mongolia	6.3483	−0.5413	6.8895	0.0000	0.0000	0.0000	0.0000	0.0000
Morocco	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mozambique	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Namibia	1.3388	0.2113	1.1275	0.0000	0.0000	0.0000	0.0000	0.0000
Nepal	74.4329	−0.0029	74.4375	0.0018	43.0448	−0.0177	43.0762	0.0137
Netherlands	0.0000	0.0000	0.0000	0.0000	38.1764	−0.0090	38.1854	0.0000
Nicaragua	52.3281	0.0040	52.3819	0.0578	24.3967	0.0258	24.4959	0.1250
Niger	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nigeria	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Norway	7.1694	−0.0028	7.1756	0.0034	41.9804	0.0009	41.8580	−0.1215
Oman	4.4126	−0.0003	4.4128	0.0000	26.1590	−0.0063	26.1652	0.0000
Pakistan	30.4262	−0.0306	30.4568	0.0000	0.0000	0.0000	0.0000	0.0000
Panama	19.0953	0.0933	18.8226	−0.1794	0.0000	0.0000	0.0000	0.0000
Papua New Guinea	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Paraguay	0.0000	0.0000	0.0000	0.0000	31.8761	0.0653	31.7728	−0.0381
Philippines	54.0918	−0.0010	54.0928	0.0000	56.6386	−0.0223	56.6609	0.0000
Poland	21.0054	−0.0013	21.0066	0.0000	34.4932	−0.0280	34.5212	0.0000
Portugal	26.1282	−0.0013	26.1295	0.0000	38.1376	−0.0294	38.1670	0.0000
Romania	0.0000	0.0000	0.0000	0.0000	5.6961	0.0154	5.7570	0.0763
Rwanda	0.0000	0.0000	0.0000	0.0000	11.4551	0.0261	11.5463	0.1173
Saudi Arabia	0.0000	0.0000	0.0000	0.0000	18.3427	−0.0295	18.3722	0.0000
Senegal	31.8184	0.0691	31.9967	0.2475	0.0000	0.0000	0.0000	0.0000
Slovak Republic	21.7400	0.0160	21.6718	−0.0522	1.8577	0.0198	1.7255	−0.1124
Slovenia	26.3791	0.0000	26.3819	0.0028	35.5002	0.0000	35.5621	0.0619
South Africa	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Spain	0.0000	0.0000	0.0000	0.0000	5.7476	−0.0139	5.8735	0.1120
Sri Lanka	55.5878	−0.0005	55.5883	0.0000	33.7308	−0.0115	33.7423	0.0000
St. Kitts and Nevis	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
St. Lucia	31.6428	0.0247	31.5377	−0.0804	1.7324	0.0306	1.5287	−0.1732
Suriname	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sweden	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Switzerland	57.7132	−0.0027	57.7192	0.0033	41.0546	0.0009	40.9359	−0.1179
Tajikistan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tanzania	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Thailand	52.6556	−0.0044	52.6708	0.0109	38.9072	−0.0267	38.9528	0.0189
Togo	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Trinidad, Tobago	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tunisia	0.0000	0.0000	0.0000	0.0000	8.8994	0.0388	8.8606	0.0000
Turkey	22.8057	−0.0011	22.8067	0.0000	48.6553	−0.0234	48.6787	0.0000
Uganda	14.3203	0.0123	40.7055	26.3974	0.0000	0.0000	61.1962	61.1962

Ukraine	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
UAE	5.3534	−0.0024	5.3531	−0.0028	27.0438	−0.0374	26.9642	−0.1170
United Kingdom	0.0000	0.0000	0.0000	0.0000	23.7600	−0.0133	23.7733	0.0000
Uruguay	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Uzbekistan	19.9724	0.0006	19.9717	0.0000	59.7668	0.0144	59.7524	0.0000
Venezuela, RB	38.2000	−0.0013	38.2028	0.0016	39.7525	0.0004	39.6965	−0.0556
Vietnam	52.2606	−0.0003	52.2612	0.0003	52.7845	0.0001	52.7732	−0.0112
Yemen, Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Zambia	35.7680	−0.0184	35.8049	0.0184	0.0000	0.0000	0.0000	0.0000
Zimbabwe	35.3227	0.0079	35.3408	0.0259	27.0798	0.0138	27.1261	0.0601

Table A3. Trade-off effects on the methane ($\boldsymbol{z_1^b}$) and nitrous oxide ($\boldsymbol{z_2^b}$) when h = −0.5 and d = (1, 1).

DMU$_j$	**Methane Emissions z_1^b**				**Nitrous Oxide Emissions z_2^b**			
	w.r.t y_1^g		**w.r.t y_2^g**		**w.r.t y_1^g**		**w.r.t y_2^g**	
	z_1^-	τ_{11}^-	z_1^-	τ_{12}^-	z_2^-	τ_{21}^-	z_2^-	τ_{22}^-
Afghanistan	11.3900	−0.0071	11.3971	0.0000	0.0000	0.0000	0.0000	0.0000
Albania	33.9745	−0.1843	34.1588	0.0000	36.9676	−0.1287	37.0963	0.0000
Algeria	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Angola	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Antigua, Barbuda	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Argentina	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Armenia	0.0000	0.0000	0.0000	0.0000	16.4509	−0.0586	16.5095	0.0000
Australia	0.0000	0.0000	0.0000	0.0000	49.3314	0.0034	49.3280	0.0000
Austria	45.9665	0.0018	45.9624	−0.0023	38.4108	−0.0006	38.4927	0.0812
Azerbaijan	0.0000	0.0000	0.0000	0.0000	11.0384	0.0073	11.0310	0.0000
Bahamas, The	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bangladesh	62.1300	−0.0001	62.1302	0.0000	54.2828	−0.0028	54.2856	0.0000
Barbados	0.0000	0.0000	0.0000	0.0000	8.4524	0.0219	8.7039	0.2734
Belarus	43.2096	−0.0124	43.2634	0.0414	40.7744	−0.0154	40.8790	0.0892
Belgium	43.5784	−0.0589	43.6373	0.0000	0.0000	0.0000	0.0000	0.0000
Belize	51.0052	0.0000	51.0033	−0.0020	33.9164	0.0000	33.8727	−0.0437
Benin	14.2538	−0.0664	14.0673	−0.2528	0.0000	0.0000	0.0000	0.0000
Bhutan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bolivia	20.7541	0.0007	20.7549	0.0015	15.4104	−0.0005	15.4113	0.0004
Bosnia, Herzegovina	34.9269	−0.0122	34.9798	0.0407	62.5537	−0.0151	62.6565	0.0877
Botswana	0.0000	0.0000	0.0000	0.0000	46.6598	−0.0158	46.6756	0.0000
Brunei Darussalam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bulgaria	7.0051	0.0009	7.0042	0.0000	31.7221	0.0210	31.7010	0.0000
Burkina Faso	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Burundi	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cambodia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cameroon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Central African Rep	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Chile	33.6993	0.0011	33.6982	0.0000	35.5376	0.0253	35.5122	0.0000
Congo, Dem. Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Congo, Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Costa Rica	61.9984	0.0001	61.9981	−0.0001	45.8673	0.0000	45.8726	0.0053

Cote d'Ivoire	12.0193	0.0043	12.0124	−0.0027	3.4958	0.0262	3.4495	−0.0202
Croatia	16.7488	0.0008	16.7480	0.0000	26.9355	0.0177	26.9179	0.0000
Cuba	5.4733	−0.0241	5.4802	−0.0173	16.9674	−0.0095	16.9217	−0.0552
Cyprus	40.0264	0.0000	40.0351	0.0087	42.0092	0.0000	42.2018	0.1926
Czech Republic	28.4080	0.0013	28.4067	0.0000	65.3085	0.0286	65.2799	0.0000
Denmark	0.0000	0.0000	0.0000	0.0000	58.9398	0.0029	58.9369	0.0000
Dominica	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Dominican Republic	0.0000	0.0000	0.0000	0.0000	18.3667	−0.0405	18.4072	0.0000
Ecuador	64.6133	0.0010	64.6111	−0.0012	54.8172	−0.0003	54.8602	0.0427
Egypt, Arab Rep.	26.8428	0.0009	26.8419	0.0000	41.7122	0.0198	41.6924	0.0000
El Salvador	0.0000	0.0000	0.0000	0.0000	30.9846	0.0044	30.9802	0.0000
Eritrea	28.1384	−0.0090	28.1474	0.0000	0.0000	0.0000	0.0000	0.0000
Estonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethiopia	0.0000	0.0000	0.0000	0.0000	24.9627	10.4356	14.5271	0.0000
Fiji	52.9614	0.0077	52.9291	−0.0245	21.6796	−0.0134	21.6349	−0.0581
Finland	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
France	0.0000	0.0000	0.0000	0.0000	39.4887	−0.0007	39.5241	0.0347
Gabon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gambia, The	12.8221	−0.0369	12.7357	−0.1233	0.3101	−0.0645	0.0887	−0.2859
Georgia	40.2571	0.0000	40.2599	0.0028	25.5848	0.0000	25.6461	0.0613
Germany	0.0000	0.0000	0.0000	0.0000	10.6897	0.0208	10.6618	−0.0072
Ghana	7.1463	−0.0142	6.9528	−0.2077	4.6209	−0.0911	4.2629	−0.4492
Greece	32.6142	−0.0321	32.7537	0.1074	41.4223	−0.0398	41.6934	0.2313
Guatemala	47.2302	−0.0007	47.2309	0.0000	24.9869	−0.0154	25.0023	0.0000
Guinea	18.7279	−0.0029	18.7129	−0.0179	0.0000	0.0000	0.0000	0.0000
Guyana	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Honduras	72.4088	0.0004	72.4084	0.0000	41.7889	0.0094	41.7795	0.0000
Hungary	0.0000	0.0000	0.0000	0.0000	88.6828	0.0311	88.6517	0.0000
Iceland	54.8234	0.0000	54.8234	0.0000	43.6820	0.0018	43.6802	0.0000
Iran, Islamic Rep.	17.4558	0.0078	0.0000	−17.4480	57.4069	0.0443	19.6190	−37.7437
Iraq	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Israel	0.0000	0.0000	0.0000	0.0000	28.9523	0.0199	28.9324	0.0000
Italy	0.0000	0.0000	0.0000	0.0000	35.6976	−0.0042	35.7364	0.0346
Jamaica	3.9417	0.0025	3.9190	−0.0203	0.0000	0.0000	0.0000	0.0000
Japan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Jordan	0.0000	0.0000	0.0000	0.0000	44.6324	−0.0005	44.6329	0.0000
Kazakhstan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kenya	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Korea, Rep.	33.3122	0.0007	33.3106	−0.0009	42.2033	−0.0002	42.2340	0.0305
Kuwait	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kyrgyz Republic	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Latvia	0.5596	−0.0151	0.4502	−0.1245	34.1123	−0.0690	33.9119	−0.2694
Lebanon	25.1225	0.0018	25.1207	0.0000	64.8823	0.0408	64.8415	0.0000
Lithuania	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Luxembourg	30.2075	−0.0369	30.2180	−0.0264	1.1175	−0.0145	1.0476	−0.0844
North Macedonia	5.9554	−0.0148	5.9622	−0.0081	28.2153	−0.0064	28.1942	−0.0275
Madagascar	32.1815	0.0019	32.1861	0.0065	40.0712	0.0034	40.0829	0.0151
Malawi	7.4059	−0.0125	7.2361	−0.1823	3.0319	−0.0799	2.7177	−0.3941
Maldives	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mali	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Malta	0.0000	0.0000	0.0000	0.0000	8.2990	−0.0085	8.3075	0.0000
Mauritius	13.5272	0.0023	13.5250	0.0000	38.8434	0.0502	38.7932	0.0000
Mexico	0.0000	0.0000	0.0000	0.0000	28.0033	0.0033	27.9731	−0.0269
Moldova	0.0000	0.0000	0.0000	0.0000	39.1064	0.0090	39.1879	0.0905
Mongolia	7.4302	0.5406	6.8895	0.0000	0.0000	0.0000	0.0000	0.0000
Morocco	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mozambique	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Namibia	0.9161	−0.2115	1.1275	0.0000	0.0000	0.0000	0.0000	0.0000
Nepal	74.4386	0.0029	74.4339	−0.0018	43.0803	0.0178	43.0488	−0.0137
Netherlands	0.0000	0.0000	0.0000	0.0000	38.1945	0.0091	38.1854	0.0000
Nicaragua	52.3201	−0.0040	52.2650	−0.0591	24.3450	−0.0259	24.2431	−0.1278
Niger	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nigeria	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Norway	7.1749	0.0028	7.1687	−0.0035	41.9786	−0.0009	42.1022	0.1227
Oman	4.4131	0.0003	4.4128	0.0000	26.1715	0.0063	26.1652	0.0000
Pakistan	30.4875	0.0307	30.4568	0.0000	0.0000	0.0000	0.0000	0.0000
Panama	18.9085	−0.0935	19.1822	0.1802	0.0000	0.0000	0.0000	0.0000
Papua New Guinea	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Paraguay	0.0000	0.0000	0.0000	0.0000	31.7452	−0.0656	31.8491	0.0382
Philippines	54.0938	0.0010	54.0928	0.0000	56.6833	0.0225	56.6609	0.0000
Poland	21.0079	0.0013	21.0066	0.0000	34.5494	0.0282	34.5212	0.0000
Portugal	26.1308	0.0013	26.1295	0.0000	38.1966	0.0296	38.1670	0.0000
Romania	0.0000	0.0000	0.0000	0.0000	5.6652	−0.0155	5.6028	−0.0780
Rwanda	0.0000	0.0000	0.0000	0.0000	11.4028	−0.0262	11.3085	−0.1206
Saudi Arabia	0.0000	0.0000	5.3588	5.3588	18.4018	0.0296	29.9140	11.5419
Senegal	31.6801	−0.0692	31.5000	−0.2492	0.0000	0.0000	0.0000	0.0000
Slovak Republic	21.7080	−0.0160	21.7774	0.0535	1.8180	−0.0198	1.9530	0.1151
Slovenia	26.3791	0.0000	26.3763	−0.0028	35.5002	0.0000	35.4371	−0.0631
South Africa	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Spain	0.0000	0.0000	0.0000	0.0000	5.7754	0.0139	5.6474	−0.1141
Sri Lanka	55.5888	0.0005	55.5883	0.0000	33.7539	0.0116	33.7423	0.0000
St. Kitts and Nevis	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
St. Lucia	31.5935	−0.0246	31.7005	0.0824	1.6713	−0.0305	1.8793	0.1774
Suriname	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sweden	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Switzerland	57.7186	0.0027	57.7125	−0.0034	41.0528	−0.0009	41.1728	0.1191
Tajikistan	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tanzania	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Thailand	52.6643	0.0044	52.6490	−0.0109	38.9607	0.0268	38.9149	−0.0190
Togo	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Trinidad and Tobago	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tunisia	0.0000	0.0000	0.0000	0.0000	8.8217	−0.0389	8.8606	0.0000
Turkey	22.8078	0.0011	22.8067	0.0000	48.7023	0.0235	48.6787	0.0000
Uganda	14.2958	−0.0123	14.3081	0.0000	0.0000	0.0000	0.0000	0.0000
Ukraine	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
United Arab Emirates	5.3583	0.0025	5.3589	0.0030	27.1187	0.0376	27.2035	0.1223
United Kingdom	0.0000	0.0000	0.0000	0.0000	23.7867	0.0134	23.7733	0.0000
Uruguay	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Uzbekistan	19.9711	−0.0006	0.0000	−19.9717	59.7380	−0.0145	16.7369	−43.0156
Venezuela, RB	38.2025	0.0013	38.1997	−0.0016	39.7516	−0.0004	39.8082	0.0562
Vietnam	52.2611	0.0003	52.2606	−0.0003	52.7843	−0.0001	52.7957	0.0113
Yemen, Rep.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Zambia	35.8049	0.0184	35.7679	−0.0186	0.0000	0.0000	0.0000	0.0000
Zimbabwe	35.3069	−0.0079	35.2883	−0.0265	27.0521	−0.0139	27.0044	−0.0615

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