Do greenhouse gas mitigation cost-effectiveness rankings based on the global warming potential favor sub-optimal allocation of resources?

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Abstract

The global warming potential $\text{GWP}_{\text{gas}}(\text{H})$ relates radiative forcing of a single pulse emission of a greenhouse gas, the absolute global warming potential $\text{AGWP}_{\text{gas}}(\text{H})$, to the respective radiative forcing of carbon dioxide over a defined time horizon H . Mitigation measures targeting short-lived climate forcers (SLCFs) or reversible measures need to be applied permanently to be effective in the long run, but cost effectiveness for a permanent application of a measure differs from a single application. We propose a concept for an absolute global warming potential of permanent yearly pulses $\text{AGWP}'_{\text{gas}}(\text{H})$, and several options for alternative indices to replace or complement the GWP: For the $\text{GWP}_{\text{gas}}(\text{H}/\text{H})$ and the $\text{GWP}^c_{\text{gas}}(\text{H}/\text{H})$ we keep the $\text{AGWP}_{\text{CO}_2}(\text{H})$ in the denominator, which allows the direct comparison with conventional estimates, while for the $\text{GWP}'_{\text{gas}}(\text{H})$ we define a new metric replacing the denominator by the $\text{AGWP}'_{\text{CO}_2}(\text{H})$. Different cost-effectiveness indicators can be defined respectively. We demonstrate the concept on the example of typical greenhouse gases emitted or removed by the agricultural sector: methane, nitrous oxide and carbon dioxide, fossil and stored as soil carbon. We show that, compared to GWP-based cost-effectiveness analysis, measures targeting soil carbon are discouraged relative to measures targeting methane, nitrous oxide and fossil carbon dioxide.

Keywords: cost-effectiveness, greenhouse gas mitigation, carbon sequestration, climate change, agriculture, global warming potential

1. Introduction

In view of the Paris Agreement commitments to keep global temperature change below 1.5-2 degrees Celsius with limited time and financial resources available, the question of cost effectiveness of potential mitigation measures is becoming increasingly important. Identification of the most cost-effective measures, however, is challenging because mitigation measures may target emissions of different greenhouse gases with different life times in the atmosphere. Furthermore, some mitigation options such as the storage of carbon in biomass or soils generally are reversible and saturate so that their effect converges towards zero after some time. We define the cost-intensity of mitigation measures as the yearly costs of a measure divided by the CO_2 equivalents¹ of the yearly mitigated emissions or the average yearly carbon removal expressed in CO_2 in case of carbon sequestration (in the following referred to as “conventional” methodology). In the literature this is generally referred to as cost-effectiveness ratio, but we propose this term as it expresses the concept better. Cost-efficiency can be defined as the reciprocal value of cost-intensity.

Recent literature raised concerns whether the conventional methodology is suitable to answer the question on how to achieve desirable long-term climate impacts at the lowest costs. A series of articles particularly address the issue of short-lived climate pollutants (SLCFs) which may have a large impact in the short run, but will have disappeared from the atmosphere within a few years (Shine et al, 2005, Shine, 2009, Cain et al., 2019, Allen et al., 2018, Lynch et al, 2020). Therefore, a mitigation activity targeting such SLCFs today will hardly affect long-term temperature changes unless the activity has a permanent character. Similarly, a mitigation activity targeting (soil) carbon

¹ usually looking at a time horizon over 100 years, using the Global Warming Potential GWP_{100}

sequestration builds-up reversible carbon pools that reach an equilibrium after some time (providing no further mitigation effect), and risking to be released again if not well managed. By contrast, long-lived greenhouse gases (LLGHGs) accumulate in the atmosphere, and the moment carrying out the mitigation activity is less relevant for the long-term effect on temperature.

Studies have developed new metrics to overcome these issues, such as the Global Temperature Change potential (GTP) or the GWP*, extending the analysis to the impact on global temperature (see Shine et al, 2009, Cain et al. 2019, Allen et al., 2018, Lynch et al, 2020) or going a step further by introducing abatement cost and damage functions, like the Global Damage Potential (GDP), the Global Cost Potential (GCP) or the Cost-effective Temperature Potential (CETP), turning the metric itself into a full cost benefit analysis or a cost-effectiveness analysis (see Johansson, 2011, Tol et al., 2012).

Here, we develop a concept for a systematic comparison of mitigation costs for mitigation measures, which allows to take into account the different dynamic characteristics of affected climate pollutants, building on radiative forcing and the global warming potential.

2. Method: Concept for the integration of permanent yearly emission pulses in cost-effectiveness analysis of mitigation measures

2.1 Definition of show-case gases, mitigation measures and introduction to basic terminology

In order to understand the climate impact of mitigation measures it is essential to understand how they influence emissions or removals and which gases are affected. We demonstrate the different nature of effects at the example of three mitigation measures:

- 1) Measure A reducing emissions of gas_A, an SLCF with a global lifetime (lt) in the atmosphere of 12 years
- 2) Measure B reducing emissions of gas_B, an LLGHG with a lifetime of 121 years
- 3) A reversible measure C stimulating the removal of CO₂ from the atmosphere (e.g. soil carbon sequestration). We assume a constant CO₂ removal rate over 20 years, no further removals after 20 years if the measure continues, while being reversed with the same rate if the application of the measure ceases.
- 4) Measure D reducing emissions of fossil CO₂.

In order to keep calculations simple, we assume that all four measures have identical yearly costs of 1 EUR, could be applied permanently over a period or just once in the initial year t_0 , and emission reductions or removals of a single application correspond to 1 kg of CO₂eq, using GWP₁₀₀

The formula for the GWP (Myhre, G., Shindell, D. et al, 2013) is:

$$(1) \quad GWP_{gas}(H) = \frac{AGWP_{gas}(H)}{AGWP_{CO_2}(H)} = \frac{\int_0^H RF_{gas}(t)dt}{\int_0^H RF_{CO_2}(t)dt}$$

H is the time horizon for which we take effects into account (for the example we use 100 years), $RF_{gas}(t)$ is the functional form for the radiative forcing over time, describing the radiative forcing in year t of an initial pulse in t_0 , and $AGWP_{gas}$ is the absolute global warming potential of the gas, which is the cumulative effect on radiative forcing over the time horizon. Let's further assume that $AGWP_{CO_2}(100)$ is exactly 1, which allows us to use GWP(100) and AGWP(100) as synonyms. If the GWP(100) 28 for gas_A and 265 for gas_B, then measures A, B and D lead to a reduction of emissions of (1/28) kg gas_A, (1/265) kg gas_B, and 1kg of CO₂, while measure C removes 1kg of CO₂ from the

atmosphere. Moreover, if we simplify the calculation assuming a constant value of $RF_{gas}(t)$ for the lifetime lt_{gas} (instantaneously disappearing after lt_{gas} years), $RF_{gas}(t)$ can be described as follows:

$$(2) \quad RF_{gas}(t \leq lt_{gas}) = \frac{GWP_{gas}(H)}{\min(lt_{gas}, H)}, RF_{gas}(t > lt_{gas}) = 0$$

Accordingly, the yearly values for RF per kg of the gases corresponds to $28 \text{ W m}^{-2} \text{ kg}^{-1} / 12 \text{ yr} = 2.33 \text{ W m}^{-2} \text{ yr kg}^{-1}$ for gas_A (SLCF) and $265 \text{ W m}^{-2} \text{ kg}^{-1} / 100 \text{ yr} = 2.65 \text{ W m}^{-2} \text{ yr kg}^{-1}$ for gas_B (LLGHG), compared to $0.01 \text{ W m}^{-2} \text{ yr kg}^{-1}$ for CO_2 .

Finally, we define the mitigation cost intensity (CI) as the ratio of the measure's cost C (in EUR) and the emission reduction E , which is the sum of the reduced emissions Q (in kg) of all gases multiplied with their respective GWPs. The mitigation cost efficiency (CE) is the reciprocal value of the mitigation cost intensity:

$$(3) \quad CI = \frac{C}{E} = \frac{C}{\sum_{gas} Q_{gas} * GWP_{gas}} = \frac{1}{CE}$$

2.2 Single pulse application of mitigation measures (show-case examples)

What would happen if we apply the four measures just in t_0 (single pulse) and then return to the default technologies in the succeeding years (see Figure 1)? Measure A would lead to an impact on RF of $(28/12) \text{ W m}^{-2} \text{ yr kg}^{-1} * (1/28) \text{ kg } gas_A = 0.083 \text{ W m}^{-2} \text{ yr}^{-1}$ for 12 years, and measure B would reduce yearly RF by $(265/100) \text{ W m}^{-2} \text{ yr kg}^{-1} * (1/265) \text{ kg } gas_B = 0.01 \text{ W m}^{-2} \text{ yr}^{-1}$ for 100 years. Measure D would have the identical impact on RF as measure B, and measure C would have the small effect as measures B and D but only for one year. In the second year the effect would be cancelled by releasing the same amount removed in the first year².

While all four measures will have a total effect of $1 \text{ kg CO}_2\text{eq}$, the annual effects are very different according to the RF values calculated, and last for different periods: after 100 years, only measures B and D still have a mitigating effect, while the effect of measure C has already disappeared after the second year.

Despite these large differences in long term effects, all four measures rate the same in conventional mitigation cost-effectiveness ranking using GWP_{100} . Correcting for reversibility reduces mitigation cost efficiency of measure C by a factor of 100. If interested only in the effect 100 years after the application of the measure, then only measures B and D have the desired impact, while for measures A and C, due to zero long term impacts, costs per unit of impact increase towards infinity.

Figure 1: Impacts of three mitigation measures on Radiative forcing over a time horizon of 100 years if applied only in the first year. Y-axis. Radiative forcing; x-axis (time). This example is normalized to $1 \text{ kg CO}_2\text{eq}$; the area of the blue bars for measures A and B are identical by definition.

² Suppose the measure would be not to plough the soil. If in the second year tillage is taken on again the soil carbon stored in the first year will be released again.

2.3 Single pulse application of mitigation measures with time weights (show-case examples)

An alternative would be to assign increasing weights to climate impacts further along the time horizon, because we can expect the marginal costs per unit of radiative forcing to increase with the absolute radiative forcing, and so the relevance of climate mitigation impacts to be higher in the future than in the presence and the contribution to mitigation more valuable than today. Equation (1) would be modified in the following way:

$$(4) \quad GWP_{gas}^w(H) = \frac{AGWP_{gas}^w(H)}{AGWP_{CO_2}^w(H)} = \frac{\int_0^H RF_{gas}(t) * w(t) dt}{\int_0^H RF_{CO_2}(t) * w(t) dt}$$

The simplest form would be a linear weighting function:

$$(5a) \quad w(t) = \alpha + \beta * t$$

However, it could be argued that the weight should only increase up to the year W (i.e. if certain mitigation objectives shall be achieved until the year W) and then remain constant. In this case the weighting function (still linear) could look like:

$$(5b) \quad w(t) = \alpha + \beta * t \quad (t \leq W), \quad w(t) = \alpha + \beta * W \quad (t > W)$$

The respective generalized formulas for the absolute global warming potential for our simplified examples would be:

$$(6a) \quad AGWP_{gas}^w(H) = \min(lt, H, S) * RF_{gas} * (\alpha + \beta * \frac{\min(lt, H, S) + 1}{2})$$

$$(6b) \quad AGWP_{gas}^w(H) = \min(lt, H, S, W) * RF_{gas} * \left(\alpha + \beta * \frac{\min(lt, H, S, W) + 1}{2} \right) + (\alpha + \beta W) * RF_{gas} * \max(\min(lt, H, S) - W, 0)$$

S denoting the time of net carbon removal (measure C), which equals one for a one-time application of a measure.

As an example we could assume W=30, which might be argued by many targets relating to 2050, a net carbon removal time of S=20, select $\alpha = 0.5$ and $\beta = 0.005$ (which guarantees a weight of 1 after 100 years) or $\beta = 0.017$ (which guarantees a weight of 1 after 30 years), and book reversibility of carbon removal correctly. Then mitigation cost intensity ratios³ change from 1/1/1/1 for the “conventional” method to 1.41/1/149/1 (weighting function type from equation 5a) or 1.52/1/180/1 (weighting function type 5b), for the SLCF, the LLGHG and the CO₂ stored as soil carbon respectively.

2.4 Permanent application of mitigation measures for the time horizon H (show-case examples)

What changes if instead we apply the measures not just in the first year, but for the whole period of 100 years (see Figure 2)? Each of the four measures creates costs of 100 EUR if we apply an interest rate of zero. The yearly impact of measure A increases for the first 12 years, then the disappearance of the effect from former years cancels new effects from the measure in later years, keeping the impact stable after 12 years. Measures B and D lead to a constant increase of the impact on radiative forcing, but reaches the same level of yearly impact as measure A only after 100 years. Measure C

³ The mitigation cost intensity ratios were calculated as the cost per kg of reduced emissions in terms of weighted CO₂eq (GWP_{gas}^w). Since the cost is always 1 EUR according to the assumptions used for the four measures, the cost intensity ratios are equivalent to: $\frac{1}{Q_{gas} * GWP_{gas}^w}$.

leads to increasing impacts via carbon removal for 20 years, and then keeps a constant impact at a considerably lower level than the first two measures. If we compare figure 1 and figure 2, we can see that the dynamic impact on radiative forcing (shape of the curve) over the whole time horizon is most likely between one pulse emissions of LLGHGs (measures B and D) and permanent pulses of SLCFs (measures A and C). This supports the proposal of Cain et al. 2019, Allen et al., 2018, Lynch et al, 2020 to combine permanent pulses of SLCFs and single pulses of LLGHGs within the same metric.

Calculating the impact as the sum over all yearly impacts over the period of 100 years (ignoring later effects), mitigation cost intensities for the four measures change to 1.06/2/5.6/2 compared to values based on single pulse emission effects measured with GWP_{100}^4 .

Figure 2: Impacts of three mitigation measures on Radiative forcing over a time horizon of 100 years if applied for the whole period. Y-axis. Radiative forcing; x-axis (time).

2.5 Replacing constant radiative forcing functions by realistic formulas for CH₄, N₂O and CO₂: Single pulse application

In order to achieve more accurate values, we have to relax the assumption of constant radiative forcing and replace it by the respective functional forms usually applied in the literature. Moreover, we need to abandon the assumption of the equality of the absolute global warming potential (AGWP) and the global warming potential (GWP). If we consider methane and nitrous oxide as our SLCF and LLGHG, respectively, and target measure C to soil carbon sequestration we can keep the other assumptions. Remember that soil carbon sequestration is a process going on for a limited period (IPCC assumes generally 20 years in the 2006 guidelines), converging towards a new soil carbon equilibrium, and the process is reversible in the sense that if you return to the former farm practice all the carbon sequestered will be lost again with a long term effect of almost zero.

The absolute global warming potential (AGWP) can be expressed as⁵:

$$(7a) \quad AGWP_{CO_2}(H) = \int_0^H RF_{CO_2}(t)dt = A_{CO_2} * \left\{ a_0 * H + \sum_i^L a_i * \tau_i * \left(1 - e^{-\frac{H}{\tau_i}} \right) \right\}$$

$$(7b) \quad AGWP_{CH_4}(H) = \int_0^H RF_{CH_4}(t)dt = (1 + f_1 + f_2) * A_{CH_4} * lt_{CH_4} * \left(1 - e^{-\frac{H}{lt_{CH_4}}} \right)$$

$$(7c) \quad AGWP_{N_2O}(H) = \int_0^H RF_{N_2O}(t)dt = A_{N_2O} * \left(1 - 0.36 * (1 + f_1 + f_2) * \frac{RE_{CH_4}}{RE_{N_2O}} \right) * lt_{N_2O} * \left(1 - e^{-\frac{H}{lt_{N_2O}}} \right)$$

⁴ This is calculated as the cost of the measure divided by the accumulated impact on radiative forcing, what we will define as $AGWP'_{gas}$ later in the text (shaded area in figure 2). Note that we do not relate to $AGWP'_{CO_2}$ but $AGWP_{CO_2}$ (single pulse), which is equal to one in our example, and, therefore allows us to use the absolute values of AGWP and $AGWP'$ equivalent to GWP and GWP' . We show the calculation on the example of gas A for H=100, with a life time of 12 years and an RF of 0.083 W m⁻²yr⁻¹. For the first 12 years the yearly impact on radiative forcing is increasing because the impacts of the yearly pulses accumulate. So, the accumulated $AGWP'$ for the first 12 years is: 1*0.083+2*0.083+...+12*0.083=6*0.083=6. For the remaining 88 years the yearly impact remains constant, which accumulates to: 88*12*0.083=88. The sum gives 94. The cost for the application of measure A is 100, and 100/94=1.06.

⁵ see Chapter 8 Anthropogenic and Natural Radiative Forcing, Supplementary Material Appendix 8.A from IPCC Fifth Assessment report, Climate Change 2013: The physical Science base

AGWP describes the effect of a single pulse in t_0 , and our examples are chosen in a way that for a time horizon of 100 years the values of the saved emissions for the three gases would be exactly 1 kg of CO₂eq. For measure C, however, only a small part (0.0185 kg) of a comparable measure targeting the reduction of CO₂ emissions from fossil fuels would be realized due to the reversibility of the sequestration effect⁶. This is equivalent to an underestimation of the cost intensity by a factor of 54.19 if calculated conventionally (see also table 1).

With the two weighting functions discussed above the formulas would change to:

$$(8a) \quad AGWP_{CO_2}^w(H) = A_{CO_2} * \left\{ a_0 * \left(\alpha * H + \frac{\beta * H^2}{2} \right) + \alpha * \sum_i^3 \tau_i * a_i * \left(1 - e^{\frac{-H}{\tau_i}} \right) + \beta * \sum_i^3 \tau_i^2 * a_i * \left(1 - e^{\frac{-H}{\tau_i}} \right) - \beta * \sum_i^3 \tau_i * H * a_i * e^{\frac{-H}{\tau_i}} \right\}$$

$$(8b) \quad AGWP_{CH_4}^w(H) = (1 + f_1 + f_2) * A_{CH_4} * lt_{CH_4} * \left\{ \alpha + \beta * lt_{CH_4} - (\alpha + \beta * lt_{CH_4} + \beta * H) * e^{\frac{-H}{lt_{CH_4}}} \right\}$$

$$(8c) \quad AGWP_{N_2O}^w(H) = A_{N_2O} * \left\{ 1 - 0.36 * (1 + f_1 + f_2) * \frac{RE_{CH_4}}{RE_{N_2O}} \right\} * lt_{N_2O} * \left\{ \alpha + \beta * lt_{N_2O} - (\alpha + \beta * lt_{N_2O} + \beta * H) * e^{\frac{-H}{lt_{N_2O}}} \right\}$$

Or

$$(9a) \quad AGWP_{CO_2}^w(H) = A_{CO_2} * \left\{ a_0 * \left(\alpha * H + \beta * H^2 - 2 * \beta * H * W + \frac{3 * \beta * W^2}{2} \right) + \alpha * \sum_i^3 \tau_i * a_i * \left(1 - e^{\frac{-W}{\tau_i}} \right) + \beta * \sum_i^3 \tau_i^2 * a_i * \left(1 - e^{\frac{-W}{\tau_i}} \right) - \beta * \sum_i^3 \tau_i * W * a_i * e^{\frac{-W}{\tau_i}} + (\alpha + \beta * (H - W)) * \sum_i^3 \tau_i * a_i * \left(e^{\frac{-W}{\tau_i}} - e^{\frac{-H}{\tau_i}} \right) \right\}$$

$$(9b) \quad AGWP_{CH_4}^w(H) = (1 + f_1 + f_2) * A_{CH_4} * lt_{CH_4} * \left\{ \alpha + \beta * lt_{CH_4} - \beta * (lt_{CH_4} + 2 * W - H) * e^{\frac{-W}{lt_{CH_4}}} - (\alpha + \beta * (H - W)) * e^{\frac{-H}{lt_{CH_4}}} \right\}$$

$$(9c) \quad AGWP_{N_2O}^w(H) = A_{N_2O} * \left\{ 1 - 0.36 * (1 + f_1 + f_2) * \frac{RE_{CH_4}}{RE_{N_2O}} \right\} * lt_{N_2O} * \left\{ \alpha + \beta * lt_{N_2O} - \beta * (lt_{N_2O} + 2 * W - H) * e^{\frac{-W}{lt_{N_2O}}} - (\alpha + \beta * (H - W)) * e^{\frac{-H}{lt_{N_2O}}} \right\}$$

We can show the effects on mitigation cost intensities for our four measures in the following table for different values of α and β (all combinations are selected in a way that guarantees a weight of 1 after 100 years/30 years) and the two weighting functions (W assumed to be 30 years):

Table 1: Mitigation cost intensities for measures A, B, C and D if weighting functions are used giving higher weights to later impacts on radiative forcing. We use a $GWP^w(100)$ equivalent to $AGWP_{gas}^w(H)/AGWP_{CO_2}^w(H)$; $H=100$, $W=30$.

The lower the value for α the higher the preference for impacts later in time, and the more the weighting will favour measures with long term impacts. Moreover, the impact of the weighting is lower if we chose the weighting function increasing only up to W. A weighting with an average α of 0.5 and a correct booking of reversibility of soil carbon sequestration would change mitigation cost

⁶ We apply equation 5a with a time horizon H of 1 year assuming that the carbon sequestered in year 1 will be released in year 2, and relate it to the AGWP₁₀₀ of CO₂ (equation 5a with a time horizon of 100 years).

intensities from originally 1/1/1/1 to 1.29/0.66/77.87/1 or 1.75/0.66/139.58/1 for the two different weighting functions, respectively, as compared to an equivalent measure targeting the mitigation of fossil CO₂.

2.6 Global warming potential for permanent pulses

For the effect of a yearly pulse over the whole period H we have to modify the formulas 7a-7c. Ignoring changes and interactions over time we get:

$$(10) \quad AGWP'_{gas}(H) = \sum_{h=0}^H \int_0^h RF_{gas}(t) dt = \sum_{h=0}^H AGWP_{gas}(h)$$

Figure 3 shows the accumulation of the single radiative forcing functions of a yearly application of a measure reducing emissions of a certain gas. Each single curve represents the impact on radiative forcing over time for a single year's pulse. The total impact of the permanent measure is the sum over all curves.

Figure 3: Accumulation of impacts of yearly pulses on radiative forcing in the long run. The first pulse starts in t_0 , the second in t_1 etc.

Substituting AGWP in equation 10 by the explicit equations 7a-7c (see Appendix) leads to:

$$(11a) \quad AGWP'_{CO_2}(H) = A_{CO_2} * \left\{ a_0 * \frac{H*(H+1)}{2} + \sum_i^L a_i * \tau_i * \left(H + 1 - e^{-\frac{H}{\tau_i}} * \frac{1 - e^{-\frac{H+1}{\tau_i}}}{1 - e^{-\frac{1}{\tau_i}}} \right) \right\}$$

$$(11b) \quad AGWP'_{CH_4}(H) = (1 + f_1 + f_2) * A_{CH_4} * lt_{CH_4} * \left(H + 1 - e^{-\frac{H}{lt_{CH_4}}} * \frac{1 - e^{-\frac{H+1}{lt_{CH_4}}}}{1 - e^{-\frac{1}{lt_{CH_4}}}} \right)$$

$$(11c) \quad AGWP'_{N_2O}(H) = A_{N_2O} * \left(1 - 0.36 * (1 + f_1 + f_2) * \frac{RE_{CH_4}}{RE_{N_2O}} \right) * lt_{CH_4} * \left(H + 1 - e^{-\frac{H}{lt_{N_2O}}} * \frac{1 - e^{-\frac{H+1}{lt_{N_2O}}}}{1 - e^{-\frac{1}{lt_{N_2O}}}} \right)$$

For soil carbon sequestration we keep the assumption of a 20 years storage time. So, the formula changes to (S being the period with a positive net storage of soil carbon):

$$(12a) \quad AGWP'_{CO_2_{soil}}(H) = \sum_{h=H-S-1}^H \int_0^h RF_{gas}(t) dt = \sum_{h=H-S-1}^H AGWP_{gas}(h)$$

$$(12b) \quad AGWP'_{CO_2_{soil}}(H) = A_{CO_2} * \left\{ a_0 * \frac{S*(2H-S-1)+2H}{2} + \sum_i^L a_i * \tau_i * \left(S + 1 - e^{-\frac{H}{\tau_i}} * \frac{1 - e^{-\frac{S+1}{\tau_i}}}{1 - e^{-\frac{1}{\tau_i}}} \right) \right\}$$

Table 2 shows the results for AGWP' compared to AGWP for two different time horizons⁷, while table 3 compares different measures for the global warming potential. $GWP_{gas}(H)$ is the classical Global Warming Potential as defined in equation 1. Furthermore, we define $GWP_{gas}(H/H)$ as the

⁷ For the quantification of AGWP' we use the following parameters values: The values for A_{CO_2} , A_{CH_4} , and A_{N_2O} (radiative efficiency per kg of gas) are 1.76E-15, 1.28E-13, and 3.85E-13. They are based on values for RE_{CO_2} , RE_{CH_4} , and RE_{N_2O} from table 8.A.1, Chapter 8 Anthropogenic and Natural Radiative Forcing, Supplementary Material Appendix 8.A from IPCC Fifth Assessment report, Climate Change 2013: The physical Science base. Similarly, $f_1=0.5$, $f_2=0.15$ and average lifetimes $lt_{CH_4}=12$ and $lt_{N_2O}=121$ come from the same chapter of the report. Values for $a_0=0.2173$, $a_1=0.2240$, $a_2=0.2824$, $a_3=0.2763$, $\tau_1=394.4$, $\tau_2=36.54$, $\tau_3=4.304$ were taken from Joos et al (2013), table S₁ from the supplementary material, multi-model mean.

global warming potential of a gas for a permanent equal yearly pulse of a gas, always measured in conventional CO₂ equivalents in order to allow the direct comparison to impacts of single pulses:

$$(13a) \quad GWP_{gas}(H/H) = \frac{AGWP'_{gas}(H)}{AGWP_{CO_2}(H)}$$

$$(13b) \quad GWP_{gas}^c(H/H) = GWP_{gas}(H/H) \text{ for } lt_{gas} < H \text{ or } S < H$$

$$GWP_{gas}^c(H/H) = GWP_{gas}(H) * H \text{ for } lt_{gas} \geq H \text{ and } S \geq H$$

A yearly pulse of 1 kg fossil CO₂ mitigation over 100 years leads to a 56 times higher reduction of radiative forcing over those 100 years compared to a single pulse of 1 kg CO₂ at the beginning of the period. Note that it is less than 100 times because the impacts of the pulses in the later years have a lower impact than pulses in the first years since we count the impacts only up to the end of the time horizon H. The impact of a permanent pulse of 1 kg CH₄ is 2509 times, for 1 kg N₂O 15139 times higher, while a permanent application of a measure targeting soil carbon sequestration reduces only 19 times more CO₂ than a single pulse of a measure targeting fossil CO₂. For periods of 20 and 500 years the values change accordingly.

The lower impact of later pulses, particularly for LLGHGs, can be considered a weakness of the GWP(H/H), because it leads to a bias for LLGHGs. Moreover, as demonstrated in figures 1 and 2, the similarity of the shape of radiative forcing curves between single pulses of LLGHGs and permanent pulses of SLCFs implies that the impact of a permanent pulse of LLGHGs may be reasonably approximated by the value of AGWP_{gas}(H) multiplied with the time horizon H, avoiding the mentioned bias. This is what Allen et al. (2018), Cain et al. (2019), and Lynch et al. (2020) propose. One of the advantages of GWP(H/H) is that we keep AGWP_{CO₂}(H) as the reference, which allows the comparison and combined use of GWP(H) and GWP(H/H). We, therefore, define an alternative global warming potential for permanent pulses, which uses the GWP(100/100) for SLCFs with an average life time lower than the time horizon H (lt<H), and the GWP(100)*H for LLGHGs (lf>=H). Carbon sequestration is treated like SLCFs if the period of sequestration is lower than the time horizon H (S<H). We call this alternative Global warming potential for permanent pulses GWP^c(100/100). As can be seen from table 3, for LLGHGs the GWP^c(H/H) is considerably higher than the GWP(H/H). Note that for a time horizon H=20, only methane is considered an SLCF, while for a time horizon of H=500 all gases except fossil CO₂ can be considered SLCFs.

2.7 New metric for global warming potentials of permanent mitigation pulses

Finally, we define GWP' as a new metric entirely based on the absolute global warming potentials of permanent pulses:

$$(14) \quad GWP'_{gas}(H) = \frac{AGWP'_{gas}(H)}{AGWP'_{CO_2}(H)}$$

This would lead to values of 44.7 (CH₄), 269.9 (N₂O), and 0.34 (sequestration) for a time horizon of 100 years, 97.1 (CH₄), 251.1 (N₂O), and 1 (sequestration) for a time horizon of 20 years, and 14.1 (CH₄), 181.2 (N₂O), and 0.07 (sequestration) for a time horizon of 500 years. So, the GWP' of a permanent yearly pulse of methane over 100 years is 57% higher than the respective GWP of a single pulse, while the values for N₂O are almost identical, and for CO₂ removed via carbon sequestration it is only 34%. For methane the difference is increasing with the time horizon, starting from 16% for a time horizon of 20 years up to 73% for a time horizon of 500 years. For N₂O differences are low for time horizons of 20 and 100 years, but GWP' is 38% higher than GWP for a

time horizon of 500 years. For carbon sequestration, by contrast, the two measures are identical for a time horizon of 20 years, but GWP' steadily decreases compared to GWP, going down to 7% for a long time horizon of 500 years.

Table 2: Absolute global warming potentials for different gases for a single pulse (AGWP) and a permanent yearly pulse (AGWP') for different time horizons (20 years, 100 years and 500 years)

Table 3: Different global warming potentials for different gases for a single pulse and a permanent yearly pulse for different time horizons (20 years, 100 years and 500 years)

For the calculation of mitigation cost intensities we can use the four types of global warming potential presented in table 3. GWP(H), GWP(H/H) and GWP^c(H/H) keep the same unit (CO₂eq) in the denominator. Therefore, to guarantee comparability we keep the assumptions presented above, normalizing to mitigation cost intensities of 1 EUR per kg of CO₂eq for each of the gases when we apply the conventional global warming potential. If we apply equation 3, this means that either the yearly costs C of a reduction of a gas can be by a factor GWP_{gas} higher than the costs of reduction of 1 kg CO₂, or the quantity Q_{gas} may be by the factor GWP_{gas} lower than Q_{CO₂}. C and Q must then be kept constant when applying the different versions of Global warming potentials, but for the permanent yearly pulses we need to multiply the yearly costs C with the number of years (assuming constant yearly costs). In equivalence to the global warming potentials, we define these normalized mitigation cost intensities as NCI_{gas}(H), NCI_{gas}(H/H) and NCI^c_{gas}(H/H) with C=1 and Q=1. For GWP'_{gas}(H) the unit of the denominator changes, and so the values are not directly comparable with the others. Therefore, in order to simplify the comparison to fossil CO₂, we normalize the value H*C (cost for the whole period H) to 1:

$$(15a) \quad NCI_{gas}(H) = \frac{C}{Q * GWP_{CO_2}(H)} = \frac{C_{gas} * GWP_{gas}(H)}{Q * GWP_{gas}(H)} = \frac{C * GWP_{gas}(H)}{Q * GWP_{gas}(H)} = \frac{GWP_{gas}(H)}{GWP_{gas}(H)} = 1$$

$$(15b) \quad NCI_{gas}(H/H) = \frac{H * C * GWP_{gas}(H)}{Q * GWP_{gas}(H/H)} = \frac{H * GWP_{gas}(H)}{GWP_{gas}(H/H)} = H * \frac{\frac{AGWP_{gas}(H)}{AGWP_{CO_2}(H)}}{\frac{AGWP'_{gas}(H)}{AGWP'_{CO_2}(H)}} = H * \frac{AGWP_{gas}(H)}{AGWP'_{gas}(H)}$$

$$(15c) \quad NCI^c_{gas}(H/H) = NCI_{gas}(H) \text{ for } lt_{gas} \geq H \text{ and } S \geq H$$

$$NCI^c_{gas}(H/H) = NCI_{gas}(H/H) \text{ for } lt_{gas} < H \text{ or } S < H$$

$$(15d) \quad NCI'_{gas}(H) = \frac{H * C * GWP_{gas}(H)}{Q * GWP'_{gas}(H)} = \frac{GWP_{gas}(H)}{GWP'_{gas}(H)} = \frac{\frac{AGWP_{gas}(H)}{AGWP_{CO_2}(H)}}{\frac{AGWP'_{gas}(H)}{AGWP'_{CO_2}(H)}} = \frac{NCI_{gas}(H/H)}{NCI_{CO_2}(H/H)}$$

Table 4 shows the normalized mitigation cost intensities for the discussed gases, the three time horizons, and the three types of global warming potentials.

Table 4: Normalized mitigation cost intensities for different global warming potentials, gases and time horizons (20 years, 100 years and 500 years)

Mitigation cost intensity ratios for a permanent application of the measures, NCI_{gas}(H/H), are 1.12/1.75/5.17/1.78 for a time horizon over 100 years, 1.53/1.86/1.77/1.77 for a time horizon of 20 years, and 1.01/1.29/24.18/1.77 for a time horizon of 500 years. So, among four permanently applied measures with identical conventionally measured one pulse mitigation cost intensities (1EUR/kg CO₂eq(H)), the measure reducing methane would be the cheapest on a 100 year horizon, followed by the measures targeting N₂O and fossil CO₂, while the measure targeting soil carbon would be 5 times more expensive at the end. However, for all four measures costs would be higher than the 1 EUR suggested by conventionally measured cost intensity. This is also the case for a

measure targeting fossil CO₂ (factor 1.78) because the effect of pulses later in the period will have less time to weigh in, which can be avoided with the $NCI_{gas}^c(H/H)$, changing the ratios to 1.12/1/5.17/1 for a period of 100 years, 1.53/1/1/1/ for a period of 20 years, and 1.01/1.29/24.18/1 for a period of 500 years. In contrast to the $NCI_{gas}(100/100)$, where methane has the lowest values, it becomes relatively more costly than N₂O and CO₂. If we standardize the $NCI_{gas}(H/H)$ with the measure targeting fossil CO₂ we get a relative cost intensity ratio for the four measures of 0.63/0.98/2.90/1, which corresponds to the respective values of the $NCI'(100)$. For shorter time horizons (20 years) the differences are smaller, but still methane being the cheapest followed by CO₂ and N₂O with similar values. There are no differences between fossil carbon and soil carbon sequestration in the short term. The cost intensity ratios standardized by fossil CO₂, the $NCI'(20)$, are 0.87/1.05/1/1. In the very long run (500 years) mitigation cost intensities for methane and N₂O come closer to the values based on single pulse emissions, while fossil CO₂ stays at the same level and CO₂ from soil carbon sequestration becomes very expensive. The values of the $NCI'(500)$ for the four gases are 0.57/0.73/13.63/1. Figure 4 presents the values of $NCI(H/H)$ graphically.

Figure 4: Long term application mitigation cost intensities for various measures and time horizons with equivalent standard mitigation cost intensities of 1 EUR/kg CO₂eq(100)

3. Results and discussion

How would those results change rankings of mitigation measures in terms of cost effectiveness found in literature? We focus on the agricultural sector because it is where the choice of the metric matters probably the most, given the high share of methane emissions and the role of carbon sequestration. We use mitigation cost assessments from three sources, Eory (pers comm), Perez et al (2020), and Pellerin et al (2017), applying GWP₁₀₀.

Eory (pers comm) estimates mitigation cost efficiencies for farm practices and mitigation technologies in Scotland. Perez et al (2020) compares greenhouse gas mitigation measures on the level of EU regions, while Pellerin et al. (2017) presents mitigation cost efficiencies for farm practices in France. We selected the following technologies considered most appropriate to demonstrate the impact of the proposed methodology:

- *Nitrification inhibitors* to reduce N₂O emissions from nitrogen fertilizers applied to soils by suppressing the nitrification process
- *Biogas flaring*, the collection and burning of methane from livestock manure management
- *Impermeable cover of liquid manure stores*, decreasing N₂O and CH₄ emissions from manure storage
- *Cover crops*, to reduce fertilizer application and increase soil carbon storage
- *Integrating grass leys* with crop production in a rotation to reduce fertilizer application and increase soil carbon storage
- *Fallowing of organic soils* to reduce CO₂ and N₂O emissions
- *Increased share of legumes in temporary grassland* to increase biological fixation, reduce N₂O emissions from mineral fertilizer application, and increase soil organic carbon
- *Feed additives: 3NOP, line seed or unsaturated fats* to reduce CH₄ emissions from enteric fermentation of ruminants

- *Precision farming and improved timing of mineral fertilizer application* increasing nitrogen use efficiency, and reducing N₂O emissions
- *A higher share of grain legumes in the arable crop rotation* to increase biological fixation and reduce N₂O emissions from mineral fertilizer application
- *Direct seeding* increasing soil carbon and N₂O emissions, while saving CO₂ emissions from diesel use
- *Buffer strips along waterways* reducing nitrogen losses and increasing soil carbon

Table 5 shows mitigation cost intensities (see equation 3) of the farm practices for the different versions of the Global Warming Potential presented in the previous sections. The first column uses the conventional CO₂eq for a horizon of 100 years, not taking into account the reversibility of soil carbon sequestration. This is considered in the second column, which shows the corrected effect on 100 years integrated radiative forcing if the farming practice is applied only in the first year. In the third column we apply the approach of weighted radiative forcing over time for a single pulse, using equations 9a-9c, with $W=30$, $\alpha=0,5$, and $\beta=0,017$. The fourth column calculates mitigation cost intensities for permanent pulses using the $GWP(100/100)^8$. The values are higher than cost intensities for $GWP(100)$, since emission impacts of pulses in later years have lower impacts than pulses in the first years, which affects LLGHGs stronger than SLCFS.

Since an alternative metric called GWP^* , proposed by Allen et al. (2018), Cain et al. (2019), and Lynch et al. (2020), has been discussed recently, we would like to compare our proposal also to this metric. $GWP_{gas}^*(H)$ is designed in a way which guarantees that a permanent yearly pulse of a SLCF over the whole time horizon H , generally 100 years, would equal H times the $GWP_{gas}(H)$ of the respective gas. As our proposal is based on the same assumption, a permanent yearly pulse over the time horizon H , the $GWP^*(H)$ would match the $GWP(H)$ presented in the first column of table 5. Respectively, for a time horizon of 100 years our methodology would lead to higher mitigation cost intensities than measured with the GWP^* , for all considered gases (CH₄, N₂O, CO₂). This is demonstrated by the values of $NCI_{gas}(100/100)$ in table 4. The difference would be lowest for methane (12%), followed by N₂O (75%) and CO₂ (78%), while the gap for CO₂ removed via carbon sequestration would be largest (417%) since this issue is not directly addressed with the GWP^* . Technologies targeting methane are, therefore, favored by our methodology compared to both GWP and GWP^* , due to its quick impact and the fact that the impact of late pulses of N₂O and CO₂ are only counted for a few years. As discussed in the previous section this bias for LLGHGs can be avoided by the use of $GWP^c(100/100)$. The respective mitigation cost intensities are presented in columns 7-9 of table 5.

Comparing the farm practices and technologies considered in Eory (pers comm), conventionally estimated (first column), covering slurry is the most cost efficient measure to reduce emissions while nitrification inhibitors is the most costly mitigation measure. Considering reversibility (second column) changes the ranking by increasing the mitigation cost intensities of cover crops and grass leys considerably. If we weight long term impacts higher (column 3) competitiveness of nitrification inhibitors, but also cover crops and grass leys due to their positive impacts on N₂O emissions, increases, while technologies targeting methane like 3NOP, biogas flaring and slurry cover become more expensive. In the long term application for 100 years (column 4), mitigation technologies become generally more expensive for SLCFs and LLGHGs, but in particular nitrification inhibitors affecting N₂O, a LLGHG. By contrast, measures like cover crops and grass leys affecting soil carbon sequestration become more cost efficient than for a single pulse application (corrected values)

⁸ This is to guarantee a better comparability to GWP_{100} . If applied in a study on the comparison of mitigation cost intensities the relation to $AGWP'_{CO_2}(H)$ might be applied instead.

because only a permanent implementation of those farming practice guarantees the permanent storage of carbon in soils. However, cost efficiency remains considerably lower than indicated in conventional estimates because sequestration happens only for a limited time period while the measure has to be applied permanently in order to avoid to lose the carbon stored before. If we use the $GWP^c(100/100)$, nitrification inhibitors keep the higher cost efficiency of the conventional estimates, and also cover crops and grass leys, due to the impacts on N_2O , slightly improve compared to $GWP(100/100)$, while the other farm practices stay at the level of $GWP(100/100)$.

Among the technologies considered in Perez et al. (2020), conventionally estimated, the increased share of legumes in temporary grassland is the most cost efficient measure, followed by fallowing of organic soils and nitrification inhibitors, while line seed and winter cover crops are by a factor of ten less efficient to mitigate greenhouse gas emissions. Considering reversibility of carbon sequestration, a single pulse application for one year would lead to a considerable downgrading of the increased legume share on temporary grassland (by a factor of more than 10) and a very strong decrease of cost efficiency for winter cover crops. Weighting the impact on radiative forcing turns the impact of winter cover crops on GHG mitigation to a negative value (net emission increases due to higher N_2O emissions) and reduces competitiveness of line seed feeding. On the other hand, other technologies become relatively more cost efficient. The use of the $GWP(100/100)$ makes all technologies more expensive compared to conventional measurement, but favor technologies targeting methane like line seed feeding, while technologies targeting LLCPS (better timing, precision farming, nitrification inhibitors, fallowing) become less competitive. The latter can be avoided with the $GWP^c(100/100)$, while mitigation cost intensities for practices targeting soil carbon (cover crops and a higher share of legumes in temporary grassland) stay at a high level.

For Pellerin et al. (2017), numbers in the first column slightly differ from the values in the original paper because we have recalculated the mitigation potential with the latest GWP factors (5th assessment report) for a better comparability. Conventionally estimated, direct seeding is the most cost efficient measure to mitigate greenhouse gas emissions, followed by a higher share of grain legumes and nitrification inhibitors, while feeding of unsaturated fats and buffer strips are high cost measures. Considering reversibility of soil carbon sequestration, a single pulse has considerably lower soil carbon gains for direct seeding and buffer strips, which leads to significant decreases of mitigation cost efficiencies for those two measures. Weighting later impacts stronger improves cost efficiency for nitrification inhibitors, grain legumes and buffer strips, while direct seeding will massively lose competitiveness, and feed additives will become less cost attractive too. With the $GWP(100/100)$ mitigation cost intensities increase for all measures, but less for the feed measure. Direct seeding remains considerably more expensive than grain legumes. $GWP^c(100/100)$ leads to considerably lower mitigation cost intensities than $GWP(100/100)$ except for feed additives, where the values are identical. In particular, this is the case for nitrification inhibitors.

Table 5: Mitigation cost intensity (EUR/t of CO_2eq) for some farming practices according to conventional $GWP(100)$, $GWP(100)$ corrected for reversibility, $GWP(100)$ weighted ($\alpha=0.05$, $\beta=0.017$), and long term application for 100 years

If we abandon the $AGWP_{CO_2}(H)$ as reference (which allows to stay within the metric of $GWP(H)$), we can use the $AGWP'_{CO_2}(H)$ as the new reference, ending up with mitigation cost intensities per $GWP'(H)$, presented in figure 5. Costs per kg of $CO_2'eq$ are considerably higher, since the denominator corresponds to a larger value. Therefore, a direct comparison with mitigation cost intensities using $GWP(H)$ or $GWP(H/H)$ is not meaningful.

Figure 5: Mitigation cost intensities under an alternative metric GWP'(100), relating to a permanent yearly pulse of 1 ton of CO₂ over a period of 100 years in EUR/t of CO₂'eq. Short cuts for mitigation technologies: **Eory (pers comm)**: FA1 (3NOP), NI1 (Nitrification inhibitors), SCI (Impermeable slurry covers), BF (biogas flaring), CC1 (Cover crops), GL (grass leys); **Perez et al. (2020)**: BTF (better timing of mineral fertilizer application), FH (fallowing of histosols), LG (higher share of legumes in temporary grassland), FA2 (Feed additive: Line seed), NI2 (Nitrification inhibitors), PF (precision farming), CC2 (cover crops); **Pellerin et al. (2017)**: NI3 (Nitrification inhibitors), LA (more grain legumes in crop rotation), NT (direct seeding), BS (Buffer strips), AF (Agroforestry), FA3 (Feed additive: unsaturated fats).

4. Summary and Conclusions

The global warming potential is an index measuring radiative forcing of a one pulse emission of a greenhouse gas relative to carbon dioxide over a defined time horizon. It is generally used as a common measure for the contribution of different greenhouse gases to global warming, and gives all impacts the same weight, regardless when they occur along the time path. So called SLCFs, like methane, have higher impacts in the short run, but lower impacts in the long run, while for LGHGs, like CO₂ or N₂O, the opposite is the case. For the comparison of mitigation technologies and their costs this is a challenge. If we invest a lot in the mitigation of SLCFs now, but cannot guarantee that those measures continue to be applied also in the future, we may waste money which could be better invested for long term climate policy. Similarly, even if we can guarantee a permanent application we have to consider that after a certain period we will not see additional mitigation any more while we have to continue to pay for the measure. A similar case are technologies targeting carbon sequestration in soils because of reversibility. If applied only once the gains of the first year will be quickly lost in the following years. If applied permanently, sequestration will cease after some time, while the yearly costs remain.

Here, we showed that in particular for carbon sequestration in soils conventionally measured mitigation cost efficiencies are overestimated because reversibility is not taken into account. Since for technologies targeting SLCFs and soil carbon a short term application (akin, equivalent to the one pulse concept followed by the conventional global warming potential) is not effective in mitigating global warming in the long run we propose to use long term application as the basis for the estimation and comparison of mitigation cost. As we need to reduce net emissions to zero in order to stop global warming (see Cain et al, 2019) even mitigation measures targeting LLGHGs need to be applied permanently at the end. We present a concept to quantify absolute global warming potentials for permanent yearly pulses. This is the basis for different options to integrate long term application into the current GWP metric or replace it by a new metric in order to assess cost efficiencies of mitigation technologies. The idea to use permanent pulses was already introduced by Shine et al. (2005), in the context of the Global Temperature Change Potential (GTP_s) for sustained emissions change, and reflects also the basic principle applied in the concept of the GWP*, which compares one pulse emissions for LLGHGs with permanent emission changes for SLCFs (see Cain et al., 2018., Allen et al., 2019, Lynch et al., 2020).

We see that for permanent application over a period of 100 years, mitigation cost intensities are generally higher than if estimated for a single application, for technologies increasing soil carbon even by a factor of 5. Technologies reducing methane become relatively more competitive compared to technologies reducing CO₂ and N₂O, because impacts can be achieved quicker. If we

apply the global warming potential for permanent pulses only to SLCFs and CO₂ from soil carbon, but keep the conventional measures for LLGHGs, the relatively higher cost efficiency of methane disappears, while the low efficiency of soil carbon technologies remains.

For policy makers the above might lead to the following conclusion: In the context of climate policy, subsidies for technologies targeting SLCFs and soil carbon sequestration might be restricted to those cases where long term application is guaranteed, and the decision should be based on the respective estimates of mitigation costs and potentials for permanent application. In this sense measures with higher initial costs but lower future costs might become economically more sustainable, while the commitment for a long term financing of apparently cheap technologies might be considered less attractive, in particular if targeting soil carbon sequestration.

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Figures

Figure 1

Impacts of three mitigation measures on Radiative forcing over a time horizon of 100 years if applied only in the first year. Y-axis. Radiative forcing; x-axis (time). This example is normalized to 1 kg CO₂eq.; the area of the blue bars for measures A and B are identical by definition.

Figure 2

Impacts of three mitigation measures on Radiative forcing over a time horizon of 100 years if applied for the whole period. Y-axis. Radiative forcing; x-axis (time).

Figure 3

Accumulation of impacts of yearly pulses on radiative forcing in the long run. The first pulse starts in t_0 , the second in t_1 etc.

Figure 4

Long term application mitigation cost intensities for various measures and time horizons with equivalent standard mitigation cost intensities of 1 EUR/kg CO2eq(100)

Figure 5

Mitigation cost intensities under an alternative metric GWP'(100), relating to a permanent yearly pulse of 1 ton of CO₂ over a period of 100 years in EUR/t of CO₂'eq. Short cuts for mitigation technologies: Eory (pers comm): FA1 (3NOP), NI1 (Nitrification inhibitors), SCI (Impermeable slurry covers), BF (biogas flaring), CC1 (Cover crops), GL (grass leys); Perez et al. (2020): BTF (better timing of mineral fertilizer application), FH (fallowing of histosols), LG (higher share of legumes in temporary grassland), FA2 (Feed additive: Line seed), NI2 (Nitrification inhibitors), PF (precision farming), CC2 (cover crops); Pellerin et al. (2017): NI3 (Nitrification inhibitors), LA (more grain legumes in crop rotation), NT (direct seeding), BS (Buffer strips), AF (Agroforestry), FA3 (Feed additive: unsaturated fats).

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