RESEARCH ARTICLE

A human-scale perspective on global warming: Zero emission year and personal quotas

Alberto de la Fuente¹*, Maisa Rojas²,³, Claudia Mac Lean⁴

¹ Civil Engineering Department, Universidad de Chile, Santiago, Chile, ² Geophysics Department, Universidad de Chile, Santiago, Chile, ³ Center for Climate and Resilience Research, Universidad de Chile, Santiago, Chile, ⁴ Office of Engineering for Sustainable Development, Universidad de Chile, Santiago, Chile

* aldelafu@ing.uchile.cl

Abstract

This article builds on the premise that human consumption of goods, food and transport are the ultimate drivers of climate change. However, the nature of the climate change problem (well described as a tragedy of the commons) makes it difficult for individuals to recognise their personal duty to implement behavioural changes to reduce greenhouse gas emissions. Consequently, this article aims to analyse the climate change issue from a human-scale perspective, in which each of us has a clearly defined personal quota of CO₂ emissions that limits our activity and there is a finite time during which CO₂ emissions must be eliminated to achieve the “well below 2°C” warming limit set by the Paris Agreement of 2015 (COP21). Thus, this work’s primary contribution is to connect an equal per capita fairness approach to a global carbon budget, linking personal levels with planetary levels. Here, we show that a personal quota of 5.0 tons of CO₂ yr⁻¹ p⁻¹ is a representative value for both past and future emissions; for this level of a constant per-capita emissions and without considering any mitigation, the global accumulated emissions compatible with the “well below 2°C” and 2°C targets will be exhausted by 2030 and 2050, respectively. These are references years that provide an order of magnitude of the time that is left to reverse the global warming trend. More realistic scenarios that consider a smooth transition toward a zero-emission world show that the global accumulated emissions compatible with the “well below 2°C” and 2°C targets will be exhausted by 2040 and 2080, respectively. Implications of this paper include a return to personal responsibility following equity principles among individuals, and a definition of boundaries to the personal emissions of CO₂.

Introduction

Recent studies have shown that global warming in a single year is nearly proportional to the total cumulative amount of CO₂ emitted since the pre-industrial period [1–3]. The reason for this relationship is both that the radiative forcing of CO₂ is larger than those of any other greenhouse gas and that the removal processes of CO₂ from the atmosphere require a long
time scale [4]. As a result, to achieve the “well below 2˚C” warming limit set in the Paris Agreement of 2015 (COP21) [5], the amount of cumulative CO₂ emissions since the pre-industrial era is limited, and anthropogenic CO₂ emissions eventually must cease [2–4,6–8].

Since early attempts to halt global warming, the political discussion has adopted a top-down approach focused on countries that should reduce their emissions [9–12]. Pursuant to this top-down approach, universal agreement has been partially blocked by the different perspectives of industrialised developed countries with high per-capita emissions that are historically responsible for most of the emissions, and populous developing countries with larger growth rates in per-capita emissions [9–11,13]. Recent alternatives have proposed focalising cuts in CO₂ emissions in a few leader countries as a sort of national voluntary scheme [14]. However, human consumption of goods, food and transportation are the ultimate drivers of climate change [15], and we argue that the top-down approach underestimates this fact such that together with worldwide agreements and technological upgrades, changes in human behaviour are critical to address climate change.

Part of the success of the COP21 and the rapid enforcement of the Paris Agreement can be explained by the different approach adopted in the Paris negotiations. At the UN Climate Change Conference in Durban (COP17, 2011), all countries recognised that a new universal, legal agreement needed to be developed in which all countries had shared but differential duties. This conviction materialised in the Intended National Determined Contributions (INDCs) to reduce greenhouse gas emissions that most countries delivered ahead of the COP21. Allowing each country to draft their INDCs independently, taking into account their own national circumstances, gave them the ownership that was required for the adoption of the Paris Agreement. This success highlights the importance of a “bottom-up” approach to solve the global climate change problem. Despite the success of bottom-up contributions at the country level, we argue that engagement in fighting climate change at the individual level (and therefore in human behaviour) are critical to address climate change effectively [16,17]. Part of the “grasping” problem that prevents humans from feeling responsible for the global climate change problem is related to the nature of the issue [18]. Well described as a tragedy of the commons [19], climate change is produced by the collective action of billions of individuals—many of whom are already dead, although the costs of their actions are shared among the entire population, including many not yet born. In other words, actions and consequences in the context of climate change are disjointed in both space and time, which makes it very difficult for individuals to engage in actions against global warming [18]. The personal engagement required is further inhibited by the fact that for most people, the environment alone is not a real motivation [20]. Although civic engagement is more related to human rights, community or the impact on poorer people [20], it can be catalysed by personal experiences such as car-pooling or recycling [21]. In addition, if people do not feel or see that they are personally affected by climate change, it will be more difficult to achieve the required changes [22]. Likewise, as the number of individuals who perceive changes in climate increases over time, it can be argued that the number of people who will perform specific actions against climate change will also increase [21,23]. Finally, understanding that intentions are precursors of actions, then the formulation and promotion of a specific intention would require a clear definition of the target, the situation and the time frame [20,24]. In this sense, we argue that important information and efforts required to delineate this target and time period, is still insufficient. More specifically, we propose that the definition of a personal quota of CO₂ emissions, and the estimated year in which all anthropogenic CO₂ emissions should stop (hereinafter called the zero emission year, ZEY), can help fill this gap. By determining the order of magnitude of these two parameters, a personal limit regarding emissions can be set on human activity, and each person will have the required information to evaluate his or her own personal actions against
climate change, in what is called the human-scale perspective that follows the ideas previously described for economic development and human needs [25]. The expected impact of adopting a human-scale perspective on climate change is to return the responsibility to the individual level. The proposal to define a uniform personal quota does not ignore the “common but differentiated responsibility principle” [26] upon which climate negotiations build, but is rather a first-order, idealised approximation of the goal of introducing a human-scale perspective, thereby allowing humans to “grasp” the climate change problem while connecting it to the global situation. The definition of a personal quota of CO₂ emissions is not novel as an alternative to allocate emissions among countries [27,28]; it constitutes a burden sharing option that is strongly based on equity principles among humans, without any type of differentiation between them. In this manner, our definition of the ZEY extends previous research [29], connecting personal behaviour with the planetary carbon budget and boundaries, by defining a uniform per capita fairness approach to a global carbon budget with an associated timeframe. Initially, we share the definition of fairness, which does not differentiate between, for example, warm and cold countries [29]. Such differentiations can be included based on, for example, the greenhouse development rights framework [13]. Hence, the aim of this paper is to contribute to the discussion on the urgency of adopting greenhouse gas emissions cuts on the basis of the global carbon budget, within the burden sharing framework, by defining two easily read numbers and concepts aimed at individuals.

The full set of Coupled Modelling Intercomparison Project 5 (CMIP5) simulations [30] are used in this work. We complemented the analysis with the numerical model MAGICC [2,31,32] for validating the proposed ZEY and personal quota, while adopting the Paris Agreement target of “well below 2° C”.

**Methods**

**Zero emission year and remaining global CO₂ quota**

The zero emission year is estimated as the first year in which the global mean temperature of a particular CMIP5 simulation exceeds 2°C. Time series of the global mean temperature are available in the Annex I of the fifth IPCC report [33], which numerically expresses the global temperature referring to the year 2005, when global warming since the pre-industrial era (1850–1900) was 0.61°C [33]. Each of the simulated global warming time series were smoothed with a 30-year moving average filter. An example of this definition is shown in Fig 1A, in which the dashed and solid lines correspond to the simulated global warming time series with respect to the pre-industrial era and the corresponding 30 years moving average time series, respectively, which with corresponds to the RCP 8.5 scenario simulated by the model CSIRO-O-Mk3-6-0. For this simulation, warming reaches 2°C in the year 2042, which corresponds to the zero emission year of that particular simulation. Overall, 107 out of 138 CMIP5 simulations indicate climate warming greater than or equal to 2°C; 7 of which correspond to the RCP2.6 scenarios, 36 to the RCP4.5 scenarios, 25 to the RCP6.0 scenarios, and 39 to the RCP8.5 scenarios. Fig 1B shows the frequency distribution of the zero emission year computed for the entire set of 39 simulations of the RCP 8.5 simulation, in which the shaded area in the light red colour defines the range of variation of climate warming time series of the RCP 8.5. Note that the CMIP5 simulations end in 2100 and that the 30 year moving average is not defined after 2085.

Each of the CMIP5 simulations has a corresponding time series of CO₂ emissions (fossil and industrial emissions, and land use-related emissions) defined by the four RCP scenarios [30,34]. As a consequence, the cumulative CO₂ emissions between the pre-industrial era (1850) and the zero emission year are the total cumulative emissions required to meet the
warming limit of 2°C (Fig 1C). Notice that recent studies show that a sudden stop of CO$_2$ emissions overestimates the remaining global quota [35,36]. This aspect is presented in the discussion section.

The remaining global quota after 2016 was estimated considering that the cumulative CO$_2$ emissions between the pre-industrial era (1850) and 2015 were 2094±5% Gt CO$_2$ [37]. This estimation includes the 2016 global carbon budget [37]. As a result of this estimation, a set of 107 values of the remaining global quota after 2016 were obtained, all of them equally probable. With this information, we conducted a frequency distribution analysis of the CMIP5 ensemble of opportunity associated with a particular value of the remaining global quota. The frequency distribution of the CMIP5 ensemble of opportunity [38,39], hereinafter called the ensemble of opportunity, of one of the remaining global quotas is computed as the number of simulations that have a remaining global quota larger than the value in question divided by the total number of simulations. The minimum value of the remaining global quota obtained from all of the CMIP5 simulations is used to characterise the “well below 2°C” target of COP21.

**Personal quota of CO$_2$ emissions**

Based on the remaining global quota, the definition of the personal quota requires a definition of how this remaining global quota will be spent in the remaining time to the ZEY and an
estimation of the human population ($W_p(t)$, Fig 2). The remaining global quota, $T$, can be related to the personal quota as follows:

$$T = \int_{2016}^{ZEY} Q(t) \ W_p(t) \ dt$$  \hspace{1cm} (1)$$

where $Q$ denotes the personal quota written in terms of tons of CO$_2$ yr$^{-1}$ p$^{-1}$ and $W_p$ is the world population. We use the median world population estimated by the Population Division of the United Nations [40], which estimates the present world population in 7.3 billion and the median world population in 2030, 2045 and 2060 of 8.5, 9.45 and 10.18 billion, respectively (Fig 2).

First we studied a highly idealised and worst-case scenario that considers a constant personal quota until the ZEY without the implementation of any mitigation policy or technological upgrades to reduce this value. This scenario allows us to link the ZEY and the personal quota, and to define a baseline personal quota. Then we studied more plausible scenarios that consider a linear reduction in time of the personal quota, which depends on the year at which the reduction of $Q$ starts to occur.

**Validation of ZEY and personal quota**

To validate the definition of the ZEY and the personal quota, the simplified climate-carbon cycle model MAGICC [30] was used. MAGICC stands for Model for the Assessment of Greenhouse Gas Induced Climate Change and solves a coupled ocean-atmosphere system and a world average carbon cycle model. MAGICC uses as its input time series of greenhouse gases emissions and gives as a result a time series of greenhouse gas concentrations in the atmosphere and global warming with respect to the pre-industrial period. Parameters involved in the model were calibrated for each of the CMIP5 models [30], and based on historical observations, a set of 600 probabilistic/historically constrained runs were included in MAGICC for quantifying uncertainty in the analysis [2,31,32].
MAGICC simulations start in 2000, and to construct the time series of greenhouse gas emissions that forces this model, the time series of CO\textsubscript{2} emissions from CDIAC (cdiac.ornl.gov, [37]) were used for the period between 2000 and 2015. Different scenarios of CO\textsubscript{2} emissions between 2016 and 2100 are built based on a uniform personal quota, and the time series of the median world population estimated by the United Nations [40]. With respect to the emissions of other greenhouse gases, CDIAC information shows that emissions since 2005 are well represented by the RCP8.5 scenario. Consequently, the time series of emissions of other greenhouse gases in the RCP8.5 scenario was used for the period 2005–2015 in all of the simulations. Between 2016 and 2020, a linear transition between emissions of RCP8.5 and RCP2.6 is considered, and after 2020 the time series of emissions of other greenhouse gases of the RCP2.6 scenario was used. This is because the RCP2.6 scenario is the only scenario that is coherent with the 2°C target for warming. The following scenarios are considered for the CO\textsubscript{2} emissions as a function of representative values of the remaining global quota \(T\):

- \(T = \infty\). This is the base simulation, in which CO\textsubscript{2} emissions constantly increase in time as the world population increases, considering a uniform personal quota. The time series of the median world population estimated by [40] is used for the calculation. This base simulation also considers a linear transition between the present per-capita emissions (5.59 tons of CO\textsubscript{2} yr\textsuperscript{-1} p\textsuperscript{-1}, [37]) and the personal quota that is reached in 2020.

- \(T\) for 2°C. For this target, we use the following definition: this simulation follows the pathway of \(T = \infty\) simulation and suddenly stops CO\textsubscript{2} emissions at the ZEY required to meet remaining global quota associated to the 2°C warming limit with 50% of the ensemble of opportunity. Based on this simulation, subsets of simulations were defined to study the influence of a gradual reduction in time of the personal quota. These simulations consider a constant and uniform personal quota until a certain year (2020, 2025, etc.) and then a linear reduction in the per-capita emissions in such a way that the total accumulated CO\textsubscript{2} emissions are the same for the base simulation that suddenly stops the CO\textsubscript{2} emissions.

- \(T\) for “well below 2°C” target. For this target, we use the following definition: this simulation follows the pathway of \(T = \infty\) simulation and suddenly stops CO\textsubscript{2} emissions at the ZEY required for the minimum remaining global quota, i.e., the remaining global quota for which 100% of the CMIP5 simulations reach 2°C. The same type of subsets of simulations with a gradual reduction in time of the personal quota is defined for this “well below 2°C” target simulation. These sets of simulations are coherent with the “well below 2°C” target defined at the COP21 in Paris.

The model MAGICC uses as its input a single text file that contains the time series of greenhouse gas emissions, with annual resolution. Input files of the simulations of this article are available in S1 Appendix.

Transformation from CO\textsubscript{2e} and CO\textsubscript{2}

The premise of this article is that human consumption of goods, food and transportation are the ultimate drivers of climate change. Consequently, changes in personal behaviour have a large impact on CO\textsubscript{2} emissions. With this, carbon footprint calculators can now have a different reading, for example, by allowing individuals to manage the personal carbon budget by summing up their annual emissions and then to evaluate the effectiveness of a particular action. The first limitation is that carbon footprint calculators are usually written in terms of an equivalent mass of CO\textsubscript{2}, hereinafter called CO\textsubscript{2e} (e.g., [41]), whereas the personal quota estimated here is expressed in terms of CO\textsubscript{2} emissions of fossil fuels, cement, and land use-related
emissions. In the absence of detailed research, the bulk transformation from CO$_2$e to CO$_2$ was made based on a linear fit between the specific contributions of CO$_2$ radiative forcing with respect to total radiative forcing using RCP scenarios [4]. A bulk transformation factor of 0.82 ±0.01 kg CO$_2$/kg CO$_2$e ($r^2 = 0.998$) was obtained, and the goodness of this fit is shown in Fig 3.

**Results**

**Remaining global quota and zero emission year**

The ZEY is the year in which CO$_2$ emissions should stop to avoid global warming greater than 2°C with respect to the pre-industrial era. By using the full set of CMIP5 simulations for the four RCP emissions scenarios [34], a distribution of the ZEY and thus the remaining global quota can be obtained, by finding the year in which each individual simulation reaches the 2°C warming limit and relating this year with accumulated CO$_2$ emissions. Therefore, the value is not unique and the obtained distribution is shown in Fig 4A, which shows that the RCP8.5 simulations are associated with closer zero emission years, whereas simulations of the RCP6.0 scenario provide values of the ZEY furthest away in this century. The median ZEY for scenarios RCP2.6, 4.5, 6.0 and 8.5 are 2043 (2037–2058), 2058 (2042–2069), 2062 (2047–2074), and 2043 (2033–2048), respectively. Hereinafter, numbers in brackets correspond to 84% and 16% of the ensemble of opportunity, respectively, representing the standard deviation and a 68% confidence interval. Similarly, the remaining global quota is not unique and its distribution is shown in Fig 4B, which takes into account the different climate sensitivity of the CMIP5 simulations. The median remaining global quota is 1562 Gt CO$_2$ (894–2061). The solid line in Fig 4B shows the ensemble of opportunity for reaching maximum warming smaller than 2°C as a function of the remaining global quota. The ensemble of opportunity for one remaining global quota is the number of simulations that have a remaining global quota greater than or equal to this value divided by the total number of simulations. The maximum remaining global quota was 3288 Gt CO$_2$, and the minimum was 594 Gt CO$_2$. Here, the minimum remaining global quota of 594 Gt CO$_2$ is related to the total amount of CO$_2$ emissions required to achieve...
the “well below 2°C” target. As a reference, previous studies estimated the remaining global quota since 2014 at 1500 Gt CO₂ [3], 1440 Gt CO₂ [1], and 1620 Gt CO₂ [36].

The curves of Fig 5A relate the constant personal quota and the ZEY for the 2°C target warming limit required to meet the remaining global quota associated with a given percentage of the ensemble of opportunity (red line in Fig 4B). The red line defines the limit of possible solutions given by the maximum remaining global quota estimated in Fig 4B, whereas the green curve shows the minimum remaining global quota associated with the “well below 2°C” target \( T = 594 \text{ Gt CO}_2 \). Fig 5A shows that the personal quota defines the rate at which CO₂ will be emitted. Similar to what has been recently shown [35,36], if per-capita emissions are larger, the ZEY will arrive sooner than for a smaller personal quota. Furthermore, Fig 5A can be used to quantify uncertainty in the value of the remaining global quota \( T \) in two different ways. The first way considers fixing the zero emission year, and the percentage of the ensemble of opportunity of \( T \) is transferred to the value of a constant personal quota. As a result, it is possible to obtain the distribution of the constant personal quota required by defining, for example, 2050 as the ZEY (Fig 5B). The second way of quantifying uncertainty is by fixing the value of a constant personal quota such that the ZEY can be associated with a percentage of the ensemble of opportunity of \( T \). The result obtained by defining a constant personal quota of 5.0
tons of CO$_2$ yr$^{-1}$ p$^{-1}$ is shown in Fig 5C, and indicates that for the median remaining global quota ($T = 1562$ Gt CO$_2$) the corresponding ZEY is 2051, with a minimum value of 2030 associated with the “well below 2°C” target ($T = 594$ Gt CO$_2$).

Given that the personal quota and the ZEY are complementary quantities, the final recommendation related to the personal quota is more likely to involve a socio-political definition than a scientific computation. For this definition, we looked at the general trend of historical and projected per-capita emissions. Fig 6 shows the time series of the world average per-capita emissions published by the CDIAC (cdiac.ornl.gov, magenta circles), the historical emissions of the CMIP5, and per-capita emissions associated with the RCP scenarios and the corresponding time series of world population [40]. First, Fig 6 shows that in recent years the world has followed the RCP8.5 pathway [37], which is associated with the largest personal quota, thus explaining the earlier zero emission years obtained in Fig 4A. However, the long-term
perspective, given by historical per-capita emissions estimated based on the CMIP5 information (black line Fig 6) and the CDIAC data, show that per-capita emissions have remained approximately constant since 1960, with an average value of CDIAC per capita emission equal to 5.22 tons of CO$_2$ yr$^{-1}$ p$^{-1}$ with a standard deviation of 0.23 tons of CO$_2$ yr$^{-1}$ p$^{-1}$. Considering these past values and CMIP5 projections, a personal quota of 5.0 tons of CO$_2$ yr$^{-1}$ p$^{-1}$ is a representative value of both past observations and future CO$_2$ projections. The corresponding ZEY for the median remaining global quota ($T = 1562$ Gt CO$_2$) is 2051 for the target warming of 2°C, whereas the ZEY associated with the “well below 2°C” target is 2030. For simplicity, ZEY = 2050 is defined for the target warming of 2°C and 50% of the ensemble of opportunity, in case of adopting a constant personal quota.

Validation

Three simulations were made using the numerical model MAGICC to validate the results for the personal quota and ZEY associated with the “well below 2°C” and 2°C targets ($T = 594$ Gt CO$_2$ and 1562, respectively). The corresponding time series of CO$_2$ per capita and total CO$_2$ are shown in Fig 7A and 7B, respectively, where the red line corresponds to the $T = \infty$ simulation. Black lines correspond to the simulations with a constant per capita emission until the ZEY; dashed lines in green and yellow are the subset of simulations that considers a constant personal quota until 2020, 2025, and then a linear reduction of Q as preserving the total cumulated emissions associated with 50% of the ensemble of opportunity (family of yellow dashed lines, $T = 1562$ Gt CO$_2$) and the “well below 2°C” target simulation (family of green dashed lines, $T = 594$ Gt CO$_2$). Fig 7A and 7B also show the time series of observed emissions (magenta dots) and CO$_2$ emissions of the RCP8.5 and RCP2.6 scenarios (red dashed line and light blue dashed line).

As a response to the emissions scenarios of Fig 7A, 7B and 7C shows time series of global warming for the set of 600 probabilistic/historically constrained runs, where the black solid lines indicate the median time series and the coloured band indicates the standard deviation of
the results (red for the $T = \infty$ simulation, yellow for the $T = 1562$ Gt CO$_2$ simulation and green for the $T = 594$ Gt CO$_2$ simulation). Simulations with a gradual reduction in the per-capita emissions show no significant variation among each other, as observed in the fact that all of the median global warming values for the $T = 594$ Gt CO$_2$ simulation follow essentially the same pathway, with differences of approximately 0.01°C.

As expected, the $T = 1562$ Gt CO$_2$ simulations stabilise the median global warming near 2°C, thus validating the fact that the definition of a $Q = 5.0$ tons of CO$_2$ yr$^{-1}$ p$^{-1}$ and ZEY = 2050 is associated with 50% of the ensemble of opportunity. Furthermore, because the standard deviation of the global warming simulated for the $Q = 5.0$ tons of CO$_2$ yr$^{-1}$ p$^{-1}$ and ZEY = 2030 scenario is associated with global warming of less than 2°C, this scenario is coherent with the well below 2°C target defined in the Paris Agreement. The median global warming associated with $T = 594$ Gt CO$_2$ is 1.68°C, and 87% of the runs simulated global warming of more than 1.37°C.

**Fig 7.** A) Time series of per capita CO$_2$ emissions for the numerical model MAGICC, and scenario of $T = \infty$ (red line), constant $Q$ for $T = 1562$ Gt CO2 (50% of the ensemble of opportunity) and constant $Q$ for $T = 594$ Gt CO2 (“well below 2°C” target) in black lines. Subset of time series that consider a gradual reduction in per capita emissions are shown in dashed yellow ($T = 1562$ Gt CO2) and green lines ($T = 594$ Gt CO2). B) Similar to (A) for total CO$_2$ emissions. Light blue and light red dashed lines in A) and B) denotes per-capita emissions and total emissions of RCP2.6 and RCP8.5 scenarios, respectively. C) Time series of global warming associated with each scenario of A and B. The coloured band denotes the standard deviation of 600 probabilistic/historically constrained runs, whereas the solid black line denotes median global warming.

https://doi.org/10.1371/journal.pone.0179705.g007
Discussion

Zero emission year

Based on the results presented in this article, we obtain that a scenario that considers a constant personal CO$_2$ quota equal to 5.0 tons of CO$_2$ yr$^{-1}$ p$^{-1}$ and ZEY = 2030, is consistent with the “well below 2˚C” target defined at the COP21 ($T = 594$ Gt CO$_2$). The “well below 2˚C” target is defined with the 100% frequency distribution of the CMIP5 ensemble, reaching 2˚C. Furthermore, simulations for a $T = 1562$ Gt CO$_2$ show that to consider a constant personal quota equal to 5.0 tons of CO$_2$ yr$^{-1}$ p$^{-1}$ and a ZEY = 2050 is a scenario consistent with the 2˚C warming target with a 50% frequency distribution of the CMIP5 ensemble. We stress that the goal of this paper is not to provide a realistic mitigation pathway but instead to help translate the global climate change problem to a human-scale perspective related to our personal behaviour as citizens/consumers. In this sense, even though the constant personal quota scenario until the ZEY is not a realistic mitigation pathway, the ZEYs here defined are a concrete estimation of the timeframe available to eliminate anthropogenic CO$_2$ emissions.

The gradual reduction of CO$_2$ emissions in time is a more realistic mitigation pathway than a sudden stop scenario used for estimating the ZEY. If this is the case, the personal quota of 5.0 tonCO$_2$ yr$^{-1}$ p$^{-1}$ should be understood as the personal quota for the next few years, which must be reduced in time to achieve the transition towards a carbon neutral world. Here it is important to remark that the 2016 per capita emission is 5.59 tonCO$_2$ yr$^{-1}$ p$^{-1}$, such that the personal quota of 5.0 tonCO$_2$ yr$^{-1}$ p$^{-1}$ requires a 10% reduction in today’s per capita emissions. Similar results showed that CO$_2$ emissions should be eliminated by 2070 for a medium chance (frequency distribution between 50% and 66%) of limiting global warming below 2˚C; and 2050 for a medium chance of limiting global warming below 1.5˚C [35]. It is important to highlight that the sooner world average per-capita emissions start to decrease, the longer the available time to eliminate net CO$_2$ emissions (Fig 7A).

Furthermore, despite the simplified assumptions used to calculate the ZEY, it clearly identifies the human generation who will be primarily responsible for the transition towards eliminating anthropogenic CO$_2$ emissions. Climate change has been usually considered as a transgenerational problem; however, the ZEYs of 2030 and 2050 obtained for a constant personal quota show that the solution does not depend on future generations, indicating the urgency of implementing far-reaching solutions for eliminating CO$_2$ emissions.

In summary, the ZEYs obtained here can prove useful for answering three simple questions related to the climate change issue: what to do (eliminate CO$_2$ emissions), when (between 2030 and 2050), and who (the current generation).

Personal quota and personal behaviour

In this article, we showed that 5.0 tons of CO$_2$ yr$^{-1}$ p$^{-1}$ is a representative value for past and future levels in per-capita emissions of CO$_2$ (Fig 6), and we defined this value as the personal quota. First, Fig 6 shows that world average per-capita emissions have been roughly constant since 1960, suggesting the important role of the human population in the increase of CO$_2$ emissions.

The goal of this work is to help individuals with the “grasping problem” of the climate change issue, where the definition of the personal quota and ZEY should facilitate strategies to encourage pro-environmental actions. Previously mentioned strategies include reducing cognitive effort and taking advantage of social influence [42]. Consequently, these emissions boundaries are expressed in an easily readable format. For example, to reduce cognitive barriers, the results of this study can be easily communicated: "between 2030 and 2050,
anthropogenic CO\textsubscript{2} emissions should be nearly zero” or more assertively “by 2030, anthropogenic CO\textsubscript{2} emissions need to be eliminated” [43]. Furthermore, pro-environmental actions are more likely when collective associated costs and benefits are considered [42]; in this context, the existence of a uniform personal quota that reinforces the fact that climate change is attributable to the collective action of billions of people, helps individuals both to understand the climate change problem and to see the solution of a global matter from a personal perspective. Hence, with the definition of the personal quota of CO\textsubscript{2} emissions, we are proposing that individuals reinforce their understanding about boundaries to personal activities linked to greenhouse gas emissions.

Furthermore, the definition of a personal quota can help evaluate measures that can be taken individually to achieve global targets. Based on the personal quota, carbon footprint calculators could be used to measure and manage personal emissions related to food, transportation, and goods (furniture, car or electronic devices, for instance) to meet the personal quota of 5.0 tons of CO\textsubscript{2} yr\textsuperscript{-1} p\textsuperscript{-1}. Examples of CO\textsubscript{2} emissions as a function of specific actions are given in Table 1.

Likewise, the definition of the personal quota sends a clear message about the remaining budget of greenhouse gas emissions that would enable the achievement of the “well below 2°C” carbon limit.

The proposed definition of a personal quota and a ZEY contributes to the burden-sharing frameworks for individuals to solve the climate change problem. In this sense, it shares the definition of fairness that two persons who emit the same amount of CO\textsubscript{2} should equally contribute to reducing CO\textsubscript{2} emissions, regardless where they live [29]. It also helps people to visualise the link between personal actions and the planetary global budget of CO\textsubscript{2}. The issue of homogeneous personal quota has been a subject of debate [28,46], because it does not consider past responsibilities, it could be read as a right to pollute, and it does not consider that the costs of mitigation and damages are not homogeneous [47]. However, it is argued that a uniform personal quota reveals both “the common but differentiated responsibility” and the “respective capabilities” principles as it puts pressure on today’s highly emitter individuals, which on average are also individuals with higher incomes given the positive correlation between personal

### Table 1. Examples of CO\textsubscript{2} emissions as a function of specific actions. Values are presented in terms of net emission and percentages of the personal quota.

| Action                                      | Emissions         | % of personal annual quota | Reference |
|---------------------------------------------|-------------------|----------------------------|-----------|
| Filling up a car with a 50 L gas tank with fuel once a week | 6720 kg CO\textsubscript{2} | 134%                       | [44]      |
| Consumption of one kg of meat per week Beef Pig Chicken | 696 kg CO\textsubscript{2} 169 kg CO\textsubscript{2} 187 kg CO\textsubscript{2} | 13.9% 3.3% 3.7% | [45]      |
| Buying a new car                            | 4.9 ton CO\textsubscript{2} 28.7 ton CO\textsubscript{2} | 98% 574% | Examples from [41], using the transformation between CO\textsubscript{2e} and CO\textsubscript{2} of Fig 3 |
| Buying a new computer                        | 164 kg CO\textsubscript{2} 656 kg CO\textsubscript{2} | 3.3% 13.1% |                     |
| London to Glasgow (556 km) and return Plane Train | 410 kg CO\textsubscript{2} 98.4 kg CO\textsubscript{2} | 8.2% 2.0% |                     |
| Flying from London to Hong Kong              | 3.77 ton CO\textsubscript{2} | 75.4%                       |           |
| Insulating an apartment Payback over 40 years | 287 kg CO\textsubscript{2} -28.7 ton CO\textsubscript{2} | 5.7% -574% |                     |

https://doi.org/10.1371/journal.pone.0179705.t001
income and CO₂ emissions [9,13,29]. A uniform personal quota should not be interpreted as a “right to emit” more CO₂ for citizens with emissions below 5.0 tons of CO₂ yr⁻¹ p⁻¹. Such an interpretation does not consider that global warming primarily depends on the total mass of emitted CO₂, and therefore any increase in today’s per capita emissions only worsens the climate change problem and increase future mitigation costs.

In summary, this work’s primary contribution is to connect an equal per capita fairness approach to a global carbon budget, by linking personal levels with planetary levels through the definition of two numbers in an easily readable format. The ZEY (between 2030 and 2050) and personal quota (5.0 tons of CO₂ yr⁻¹ p⁻¹), are expected to help individuals to more easily comprehend and take action in regards to the climate change issue. However, the sooner the world average per-capita emissions start to decrease, the longer the available time to eliminate net CO₂ emissions.

Supporting information

S1 Appendix. Compressed file containing the input files (*.SCEN) of the different scenarios used for validating the ZEY and personal quota with model MAGICC (http://live.magicc.org/).

(ZIP)

Acknowledgments

We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP5, and we thank the climate modelling groups for producing and making available their model outputs. Thanks are given to Carolina Meruane for her useful comments on an early version of this manuscript. Finally, we would like to thank the anonymous reviewers of this manuscript for their useful and constructive comments.

Author Contributions

Conceptualization: AD.
Formal analysis: AD.
Methodology: AD.
Visualization: AD.
Writing – original draft: AD MR CM.
Writing – review & editing: AD MR CM.

References

1. Stocker TF. The Closing Door of Climate Targets. Science (80-). 2013; 339: 280–282. https://doi.org/10.1126/science.1232468 PMID: 23196911
2. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, et al. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature. Nature Publishing Group; 2009; 458: 1158–1162. https://doi.org/10.1038/nature08017 PMID: 19407799
3. Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R, et al. Persistent growth of CO₂ emissions and implications for reaching climate targets. Nat Geosci. Nature Research; 2014; 7: 709–715. https://doi.org/10.1038/ngeo2248
4. Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, et al. Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility. IPCC AR5 WG1 2013. Cambridge University Press; 2013. pp. 1029–1136.
5. UNFCCC. Conference of the Parties (COP). Adoption of the Paris Agreement. Proposal by the President. Paris Climate Change Conference—November 2015, COP 21. 2015. p. 32. FCCC/CP/2015/L.9/Rev.1

6. Matthews HD, Caldeira K. Stabilizing climate requires near-zero emissions. Geophys Res Lett. 2008; 35: L04705. https://doi.org/10.1029/2007GL032388

7. IPCC. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate. Geneva, Switzerland: IPCC; 2014.

8. Knutti R, Rogelj J. The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. Clim Change. Springer Netherlands; 2015; 133: 361–373. https://doi.org/10.1007/s10584-015-1340-3

9. Bear P, Hartje J, Haya B, Herzog A V., Holdren J, Hultman NE, et al. Equity and Green house gas responsibility. Science (80-). 2000; 289: 2287.

10. Kintisch E. Climate change. Deforestation moves to the fore in Copenhagen. Science (New York, N.Y.). 2009. p. 1465. PMID: 20007869

11. Raupach MR, Davis SJ, Peters GP, Andrae RM, Canadell JG, Ciais P, et al. Sharing a quota on cumulative carbon emissions. Nat Clim Chang. Nature Research; 2014; 4: 873–879. https://doi.org/10.1038/nclimate2384

12. van Rensen S. Getting a fair deal. Nat Clim Chang. Nature Research; 2015; 5: 513–514. https://doi.org/10.1038/nclimate2661

13. Baer P. The greenhouse development rights framework for global burden sharing: Reflection on principles and prospects. Wiley Interdiscip Rev Clim Chang. John Wiley & Sons, Inc.; 2013; 4: 61–71. https://doi.org/10.1002/wcc.201

14. Meinshausen M, Jeffery L, Guetschow J, Robiou du Pont Y, Rogelj J, Schaeffer M, et al. National post-2020 greenhouse gas targets and diversity-aware leadership. Nat Clim Chang. Nature Research; 2015; 5: 1098–1106. https://doi.org/10.1038/nclimate2926

15. IPCC. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2014.

16. Hoekstra AY, Wiedmann TO. Humanity’s unsustainable environmental footprint. Science (80-). 2014; 344: 1114–1117. https://doi.org/10.1126/science.1248365 PMID: 24904155

17. Corner A, Roberts O, Chiari S, Vo¨ller S, Mayrhuber ES, Mandl S, et al. How do young people engage with climate change? The role of knowledge, values, message framing, and trusted communicators. Wiley Interdiscip Rev Clim Chang. John Wiley & Sons, Inc.; 2015; 6: 523–534. https://doi.org/10.1002/wcc.353

18. Hardin GLB-H. The Tragedy of the Commons. Science (80-). 1968; 162: 1243–1248.

19. Howell RA. It’s not (just) “the environment, stupid!” Values, motivations, and routes to engagement of people adopting lower-carbon lifestyles. Glob Environ Chang. 2013; 23: 281–290. https://doi.org/10.1016/j.gloenvcha.2012.10.015

20. Broomell SB, Budescu D V., Por H-H. Personal experience with climate change predicts intentions to act. Glob Environ Chang. 2015; 32: 67–73. https://doi.org/10.1016/j.gloenvcha.2015.03.001

21. Blennow K, Persson J, Tomé M, Hanewinkel M, Moser S, Ekstrom J, et al. Climate Change: Believing and Seeing Implies Adapting. Krueger F, editor. PLoS One. Public Library of Science; 2012; 7: e50182. PMCID: 23185568

22. Lee TM, Markowitz EM, Howe PD, Ko C-Y, Leiserowitz AA. Predictors of public climate change awareness and risk perception around the world. Nat Clim Chang. Nature Research; 2015; 5: 1014–1020. https://doi.org/10.1038/nclimate2728

23. Fishbein M, Ajzen I. Belief, Attitude, Intention, and Behavior: An Introduction to Theory and Research. Addison-Wesley. Addison-Wesley; 1975.

24. Max-neef M a., Hopenhayn M, Hamrell S. Human Scale Development: Conception, Application and Further Reflections, Volume 1. New York and London: The Apex Press; 1991.

25. Janerio R De. United Nations Conference on Environment & Development Rio de Janerio, Brazil, 3 to 14 June 1992. Reproduction. 1992; 351. 10.1007/s11671-008-9208-3

26. Agarwal A, Narain S. Global Warming in an Unequal World: A Case of Environmental Colonialism. New Dehli, India: Centre for Science and Environment;

27. WBGU. Solving the climate dilemma: The budget approach. Special Report. Special Report., editor. Berlin: German Advisory Council on Global Change. Berlin; 2009.
29. Chakravarty S, Chikkatur A, de Coninck H, Pacala S, Socolow R, Tavoni M. Sharing global CO2 emission reductions among one billion high emitters. Proc Natl Acad Sci U S A. National Academy of Sciences; 2009; 106: 11884–8. https://doi.org/10.1073/pnas.0905232106 PMID: 19581586

30. Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society. 2012. pp. 485–498.

31. Meinshausen M, Raper SCB, Wigley TML. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. Atmos Chem Phys. 2011; 11: 1417–1456.

32. Rogelj J, Hare W, Lowe J, van Vuuren DP, Riahi K, Matthews B, et al. Emission pathways consistent with a 2°C global temperature limit. Nat Clim Chang. Nature Research; 2011; 1: 413–418. https://doi.org/10.1038/nclimate1258

33. IPCC. Annex I: Atlas of Global and Regional Climate Projections. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2013.

34. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: An overview. Clim Change. 2011; 109: 5–31.

35. Rogelj J, Schaeffer M, Meinshausen M, Knutti R, Alcamo J, Riahi K, et al. Zero emission targets as long-term global goals for climate protection. Environ Res Lett. 2015; 10: 105007. Available: http://stacks.iop.org/1748-9326/10/i=10/a=105007

36. Rogelj J, Schaeffer M, Friedlingstein P, Gillett NP, van Vuuren DP, Riahi K, et al. Differences between carbon budget estimates unravelled. Nat Clim Chang. Nature Research; 2016; 6: 245–252. https://doi.org/10.1038/nclimate2868

37. Le Quéré C, Andrew RM, Canadel JG, Sitch S, Ivar Korsbakken J, Peters GP, et al. Global Carbon Budget 2016. Earth Syst Sci Data. Copernicus GmbH; 2016; 8: 605–649. https://doi.org/10.5194/essd-8-605-2016

38. Tebaldi C, Knutti R. The use of the multi-model ensemble in probabilistic climate projections. Philos Trans R Soc London A Math Phys Eng Sci. 2007; 365.

39. Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, et al. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed TF Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.

40. Nations U. World Population Prospects: The 2015 Revision. United Nations Econ Soc Aff. 2015; XXXIII: 1–66.

41. Berners-Lee M. How bad are bananas?: The Carbon Footprint of Everything. Profile Books Plt.; 2010.

42. Steg L. Values, Norms, and Intrinsic Motivation to Act Proenvironmentally. Annu Rev Environ Resour. Annual Reviews; 2016; 41: 277–292. https://doi.org/10.1146/annurev-environ-110615-085947

43. Kronrod A, Grinstein A, Wathieu L. Go Green! Should Environmental Messages Be So Assertive? J Mark. 2012; 76: 95–102. https://doi.org/10.1509/jm.10.0416

44. Ipcc. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme [Internet]. Agriculture Forestry and Other Land Use. 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Cn3_Mobile_Combustion.pdf

45. Gerber P.J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A. & Tempio G. Tackling climate change through livestock—A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome. 2013.

46. Schuppert F, Seidel C. Equality, justice and feasibility: an ethical analysis of the WBGU’s budget approach. Clim Change. Springer Netherlands; 2015; 133: 397–406.

47. Matthews HD. Quantifying historical carbon and climate debts among nations. Nat Clim Chang. Nature Research; 2015; 6: 60–64. https://doi.org/10.1038/nclimate2774