Will Individual Actions Do the Trick? Comparing Climate Change Mitigation through Geoengineering versus Reduced Vehicle Emissions

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Key Points

- Replacing private vehicles with electric or hybrid vehicles could significantly mitigate climate change compared to geoengineering
- It is important that the portrayal of geoengineering as a safeguard does not reduce motivation for emission cuts
Abstract

Geoengineering is the focus of a large debate over potential solutions to climate change. However, in the midst of geoengineering and other large-scale proposals, such as reducing emissions at an industrial level, the role of individual actions to reduce emissions is often overlooked. Given the current and fast-paced changes we have seen as emissions are reduced by COVID-19 social distancing strategies, it is time to re-examine the impact that individual actions can have. This paper considers how one individual action (reducing carbon dioxide emissions from gasoline-fueled private vehicles), when adopted at a global scale, may have an effect that is comparable to the effects of geoengineering. This paper also argues that the role of geoengineering as a safeguard against climate change may be encouraging complacency and reducing motivation for individual action.

Plain language summary

As global temperatures continue to rise, several types of solutions are being considered to mitigate climate change. One of these is geoengineering – the large-scale use of technology coupled with and enhancing Earth’s natural processes. Geoengineering is the focus of a large debate over potential solutions to climate change since, while different geoengineering solutions may help curb CO₂ concentrations, they remain largely untested and may pose greater risks. Further, it has been argued that, as we consider geoengineering and other large-scale proposals, we risk the public losing sight of the potential for their individual actions to reduce emissions, and instead putting more faith in science to save us from climate change. Given the current and fast-paced changes we have seen as emissions are reduced by COVID-19 social distancing strategies, it is time to re-examine and reinforce the impact that individual actions can have. This
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paper considers how one individual action (reducing CO₂ emissions from private vehicles), when adopted at a global scale, may have an effect that is comparable to that of geoengineering. This paper also argues that the role of geoengineering as a safeguard against climate change may be encouraging complacency and reducing motivation for individual action.

Index terms

- 1605 Abrupt/rapid climate change (4901, 8408)
- 1616 Climate variability (1635, 3305, 3309, 4215, 4513)
- 1620 Climate dynamics (0429, 3309)
- 1630 Impacts of global change (1225, 4321)
- 1699 General or miscellaneous

Keywords

- Climate change
- Geoengineering
- Electric vehicles
- Hybrid vehicles
- Individual action
- Carbon dioxide (CO₂) emissions

1. Introduction

Global temperatures have risen by about 1.1°C from pre-industrial levels, largely due to carbon dioxide (CO₂) emissions from human activities (Ritchie & Roser, 2017). With already-implemented climate policies remaining as they are, this increase could reach as high as 3.7°C by 2100 (Ritchie & Roser, 2017), well above the goal of keeping post-industrial warming within 1.5°C (IPCC, 2018). To comply with this goal, global emissions need to be net-zero by
approximately 2050 (IPCC, 2018), adding to the sense of urgency. This leads to the question of what more can be done to combat climate change. One field of innovation that has gained a lot of attention is geoengineering, the use of technology in conjunction with Earth’s natural processes to produce a desired result, such as mitigating climate change (Caldeira et al., 2013).

Geoengineering proposals can be divided into two main categories: solar geoengineering to lower the Earth’s temperature by partially blocking sunlight, and CO₂ removal to lower greenhouse gas concentrations in the atmosphere (Caldeira et al., 2013). While geoengineering proposals in general have not been developed into useable technologies yet (Corner & Pidgeon, 2010; Suarez & van Aalst, 2017), there is significant debate over which geoengineering proposals (if any) would be the best to implement, considering factors such as relative effectiveness, cost, risk, and time requirement (Caldeira et al., 2013; Corner & Pidgeon, 2010).

Additionally, one conclusion of research into the effectiveness of geoengineering proposals compared to directly reducing greenhouse gas emissions is that solar geoengineering is not a long-term, practical solution; instead, reducing net emissions is necessary (Keith & Irvine, 2016).

However, there is not much focus on how much of a difference could be achieved through individual action (actions to help the Earth, taken by individual people) on a global scale, compared to the effects of geoengineering. The goal of this paper is to provide one such comparison. Specifically, this paper considers the individual action of reducing CO₂ emissions from private gasoline-fueled vehicles, addressing how widespread individual action could compare to geoengineering for reducing atmospheric CO₂ concentrations, both conceptually and within 4 different CO₂ reduction and electric vehicle adoption scenarios. In addition, this paper will highlight the importance of individual actions as a necessary part of the larger strategy to reduce global climate change. It has been argued that, as we consider geoengineering and other
large-scale proposals, we run the risk of the American public losing sight of the potential for
their individual actions to reduce emissions, and instead putting more faith in science to save us
from climate change (Hamblyn, 2009). We hope that by illuminating the impact that one
individual action (among many) could have on the fight to reduce CO₂ emissions, we can
reinforce the importance of individual actions in a long-term climate solution. 2. Overview of
geoengineering

Geoengineering is a complex topic because it includes a variety of proposals and factors
to take into account; a simple history and overview is presented here to provide context for this
paper. The precursor to geoengineering was originally conceived (as early as the 1830s) as a tool
for small-scale manipulation of the weather, such as changing levels of precipitation (Bonnheim,
2010). As technology developed through the twentieth century, concerns were raised about its
potential as an environmental weapon; it would not be suggested as a technology to help the
environment until the 1970s (the same decade the term “geoengineering” was coined)
(Bonnheim, 2010). Geoengineering has remained a controversial topic (regarding a number of
factors) since then, but it has steadily gathered interest and respect as a subject for research
(Caldeira & Bala, 2017). Proponents such as Keith (2013) argue that geoengineering should be
seriously considered for its potential to be a key strategy for combating climate change.

As previously mentioned, there are two main types of geoengineering (in its current
context of climate change): solar geoengineering and CO₂ removal (Caldeira et al., 2013). This
paper focuses on CO₂ removal, largely because solar geoengineering in general has more
potential for risk (Caldeira et al., 2013) and does not actually target the source of the climate
change issue (Trenberth & Dai, 2007) (ironically, the reduction in solar radiation would actually
hinder the generation of clean energy through solar power (Robock, 2008)). One proposal is to
release aerosols into the atmosphere to increase the Earth’s reflection of sunlight and reduce absorption; however, this has the potential to cause problems with the water cycle and lead to drought (Trenberth & Dai, 2007). Additionally, sudden reheating could result in the event of a failure (Caldeira et al., 2013), and it is the rapid rate of change, not the overall change, that poses the greater problem to the environment (Keith, 2013). While solar geoengineering has the potential to be very effective at lowering the Earth’s temperature (Corner & Pidgeon, 2010), it raises concerns regarding whether the risk to the environment and to people would be worth the potential benefits.

CO₂ removal, on the other hand, poses much less risk than solar geoengineering in general (Corner & Pidgeon, 2010); therefore, the focus of this paper is on proposals for CO₂ removal. These proposals are:

1. CO₂ air capture, removing CO₂ from the atmosphere and either using it or storing it (Caldeira et al., 2013).
2. Afforestation and reforestation, planting trees in non-forested lands (afforestation) or previously-forested lands (reforestation) (Vaughan & Lenton, 2011).
3. Bio-energy with carbon capture and storage (BECCS), producing energy or fuel with organic matter, and storing the CO₂ that results from this production (Vaughan & Lenton, 2011).
4. Enhanced weathering, increasing the amount of CO₂ captured by natural chemical interactions with rocks and minerals (Shepherd, 2009).
5. Biochar, storing carbon in the form of charcoal (Vaughan & Lenton, 2011).

The estimated efficacy of these proposals is summarized in Table 1. Where multiple estimates were offered by the sources, only the highest values are included in Table 1, which allows for a
more aggressive comparison with individual action. Note that the focus of this paper is on the period from the present until 2050 (because of the need for net-zero emissions by about 2050 (IPCC, 2018)), therefore the values included in Table 1 are applicable for this period except where noted. Also note that carbon capture and storage (CCS), collecting CO$_2$ at its source, such as at factories, and placing it in long-term storage (Vaughan & Lenton, 2011), is not included here as a type of geoengineering. While CCS is sometimes studied alongside the geoengineering proposals mentioned above, it is technically known as a “mitigation” strategy (Vaughan & Lenton, 2011) and does not count as geoengineering because it acts at the source of emissions without directly interacting with the climate itself (Shepherd, 2009).

Table 1

 Estimates of geoengineering effectiveness*

Estimates of the amount of CO$_2$ removed from the atmosphere, per month, by each geoengineering proposal considered.

| Type of geoengineering                                      | Reduction of CO$_2$ in atmosphere (Tg/month) | Source                                                                 |
|-------------------------------------------------------------|---------------------------------------------|------------------------------------------------------------------------|
| CO$_2$ air capture                                          | 3083**                                      | Chen & Tavoni (2013)                                                   |
| Afforestation/reforestation                                 | 1008***                                     | Crusius (2020); cites National Academies of Sciences, Engineering, and Medicine (2019) |
| Bio-energy with carbon capture and storage (BECCS)          | 833                                         | Williamson & Bodle (2016); cites IPCC (2014)                           |
| Enhanced weathering                                         | 333                                         | Streffler et al. (2018)                                                |
| Biochar                                                     | 171                                         | Vaughan & Lenton (2011); cites Lehmann et al. (2006)                    |

* Upper limits are provided where multiple estimates were available.
** This rate will likely not be applicable until around the year 2100, when CO$_2$ air capture may reach its maximum deployment, according to modeling by Chen & Tavoni (2013). For this
reason, the rate is shown as a dashed line in Figure 1 (the focus of this paper is on the period from the present until 2050). The year of maximum deployment is based on the assumption that, realistically, CO$_2$ air capture will not be deployed on a global scale until at least 2065 because other strategies will be implemented first (Chen & Tavoni, 2013). 3083 Tg/month is the maximum rate; the average rate (over the course of global deployment, until the maximum rate is reached) is estimated to be 1,333 Tg/month (Chen & Tavoni, 2013). *** A range of estimates were cited by Crusius (2020), with a maximum of 1008 Tg/month (cites National Academies of Sciences, Engineering, and Medicine, 2019) and a minimum of 43 Tg/month (cites Fuss et al., 2018).

Besides efficacy, there are many other factors that interplay with the benefits and feasibility of CO$_2$ removal proposals, and a great deal has been written on this (Caldeira et al., 2013; Corner & Pidgeon, 2010; Shepherd, 2009; Vaughan & Lenton, 2011). While CO$_2$ removal, as previously mentioned, is generally viewed as posing very low risk (Shepherd, 2009), it can still be costly and generally requires a long time to have a significant effect (see Table 2 for a high-level overview of costs and time requirements). Here it is important to stress the need for early and quick intervention due to the time lag between emissions and their effects on the climate (Hansen et al., 2005).

For this paper we do not focus on whether something is difficult or of low feasibility as there is no clear answer to this, and because we argue that even difficult solutions must be put on the table and evaluated in order to reach the aggressive, yet necessary, climate change mitigation goals that the world has set. Instead, it is our intention to demonstrate the importance of individual solutions, via one example out of many, alongside other technological advancements.

Table 2

Estimates of geoengineering costs and time factors

Estimate ranges of the costs of geoengineering compared to the amount of CO$_2$ removed from the atmosphere; general overview of factors that affect timeline (requirements before deployment, rate of effect).
| Type of geoengineering             | Cost range (USD/tCO₂)                      | Time factors (Shepherd, 2009)                                                                 |
|-----------------------------------|-------------------------------------------|-----------------------------------------------------------------------------------------------|
| CO₂ air capture                   | 136-1000                                   | More research and infrastructure needed before significant deployment; slow to have significant effect |
|                                   | (Chen & Tavoni, 2013; cites House et al., 2011; Keith et al., 2005) |                                                                                               |
| Afforestation/reforestation       | 0.27-2.18                                  | Ready for significant deployment; slow to have significant effect                              |
|                                   | (Torres et al., 2010)                      |                                                                                               |
| Bio-energy with carbon capture and storage (BECCS) | 0-1000                                     | More research needed before significant deployment; slow to have significant effect            |
|                                   | (Harding & Moreno-Cruz, 2019; cites Kriegler et al., 2013; Shepherd, 2009) |                                                                                               |
| Enhanced weathering               | 60-200                                     | More research and infrastructure needed before significant deployment; slow to have significant effect |
|                                   | (Streffer et al., 2018)                    |                                                                                               |
| Biochar                           | 221-345                                    | More research needed before significant deployment; slow to have significant effect            |
|                                   | (Bach et al., 2016)                        |                                                                                               |

In the midst of the geoengineering debate, the COVID-19 pandemic caused the shutdown of many industries and a drastic reduction in travel. While the global pandemic has had undeniably devastating effects on human life and well-being, the environment experienced a dramatic positive change. Specifically, as workplaces and travel slowed down, daily global CO₂ emissions were reduced by 17%, with approximately half of this decrease coming from surface transport (which includes private vehicles) (Le Quéré et al., 2020). While not minimizing the terrible impact that COVID-19 has had on human life and economies, one lesson from this pandemic is that reductions in surface travel can have a large influence on CO₂ emissions. This leads us to the question of whether we should refocus our investigation of climate change initiatives to study the impact of individual actions. Specifically, here we examine how the efficacy of a reduction in miles driven by each motor vehicle each month, and a transition to alternate fuel sources, would compare to various geoengineering techniques. We select the
ground transportation industry as an example of an individual action because:

1. The transportation sector is one of the largest contributors to greenhouse gas emissions (16% of global emissions in 2016) with ground transportation making up approximately three quarters of this (Ritchie, 2016) and potentially being the easiest to manipulate (Mazur et al., 2018).

2. The impacts of reduced driving have become apparent to the lay public during the COVID-19 pandemic, thus providing popularized evidence of the importance of this solution to meeting climate goals (Cruickshank, 2020; Jaramillo, 2020; Simon, 2020).

3. Research suggests that emissions from road transportation must be greatly reduced as part of any feasible solution to reduce global emissions (IEA, 2011, 2015a, 2015b, 2016; Kahn Ribeiro et al., 2007; Mazur et al., 2018; Palencia et al., 2017). In our analysis, we include both a reduction in gasoline-fueled miles driven, and also a shift to hybrid and electric vehicles, as this shift to electricity-fueled vehicles (plug-in hybrids, battery electric, and hydrogen fuel cell vehicles) is arguably necessary to achieve 2050 climate goals (IEA, 2011, 2015a, 2015b, 2016; Kahn Ribeiro et al., 2007; Mazur et al., 2018; Palencia et al., 2017; van Mierlo & Maggetto, 2007).

It is not our intent to rule out one strategy versus another, and we recognize that both geoengineering and individual action based solutions occurring simultaneously would likely yield greater results (Keith (2013) agrees that geoengineering should not be the only action taken against climate change). We argue that it is important that the debate over techniques of geoengineering not overshadow the differences that individual actions can make.
3. Methods

3.1 Focus and assumptions

In order to compare the potential effects of geoengineering versus individual action, it is necessary to consider effects that can be directly compared, quantitatively. For this reason, this paper compares the reduction of CO$_2$ in the atmosphere due to CO$_2$ removal geoengineering techniques versus that due to individual action. Since the individual action considered here is reducing the number of gasoline-fueled miles (“gas-fueled miles”) driven by all private motor vehicles currently on the road, globally, we consider this being accomplished in two main ways:

1. People reduce the distance they travel in private gasoline-fueled vehicles (“gas vehicles”). This may take the form of walking or biking to a destination instead of driving, taking public transport or carpooling, or choosing not to go to a destination at all.

2. People drive the same distance but use electricity as the source of energy. This may be accomplished by driving either fully electric vehicles (EV) or hybrid vehicles (HV) (which run on electricity or gasoline, or both at once (van Vliet et al., 2011)). Driving EV or HV allows for a greater reduction in gas-fueled miles because people can still drive the distance they need, while producing less emissions than driving the same distance in a gas vehicle.

In estimating the reduction in CO$_2$ emissions due to this individual action, several underlying assumptions are made:

1. The total number of private gas-fueled vehicles on the road equals the total number sold worldwide over the course of 10 years (2010-2019 for the purposes of this paper). There is significant uncertainty in this estimate, given a lack of data on how long each
individual vehicle is in use. It is assumed that private vehicles are used for an average of 10 years (the average age of passenger vehicles in the European Union was 11.1 years in 2017 (acea.be, 2019, cites IHS Markit). Additionally, it is assumed that all of these vehicles are completely fueled by gasoline; although a small percentage are fueled by diesel (about 1.5% in the US in 2014 (Chambers & Schmitt, 2015)), and a small percentage are EV and HV (about 2.1% in the 2018 US market (bts.gov, 2019)).

2. There are no additional emissions associated with replacing gas vehicles with EV or HV. It is assumed that, for this individual action, people choose to purchase EV or HV as it comes time to replace their gas vehicles anyway, following the possible pathways outlined in Figure 2. Assuming that new vehicles will be produced anyway, and that emissions caused by vehicle production are approximately the same for gas vehicles, EV, and HV, this results in no additional emissions from the transition from gas vehicles to EV and HV.

3. Everyone who owns a private motor vehicle will actively reduce their gas-fueled miles driven by a given number $X$ miles. This value will not be exactly the same for every person; it is simply assumed that the total reduction in gas-fueled miles, divided by the total number of private vehicles, gives an average of $X$ miles reduced per vehicle.

4. There are no additional emissions if a person takes public transport or carpools. It may be assumed that an additional passenger on public transport or in a carpool will not result in an extra trip made by the vehicle, and that if there is any reduction in efficiency due to the weight of the extra passenger, then this change is negligible.

5. The emissions from powering EV and HV are less than those of gas vehicles. There are emissions associated with generating the electricity to power EV and HV; however these
emissions vary widely based on the source of the electricity generation and on the time of day during which the vehicle is charged (van Vliet et al., 2011). This paper also assumes that, while running on electricity, HV use no gasoline. However, HV often use electricity and gasoline simultaneously to increase energy efficiency (van Vliet et al., 2011).

6. The emissions are constant for each private motor vehicle and for each mile driven. Despite the variance in efficiency and emissions for different vehicles, driving patterns, and speeds, for this calculation it is assumed that the average gas-fueled mile driven results in the emission of 404 grams of CO$_2$ (epa.gov, 2018). The emissions from EV and HV are also assumed to be constant; however, these values may likewise vary (especially for HV because different ratios of gasoline to electricity may be used at any given time (van Vliet et al., 2011)).

7. People continue to drive the same distance in EV as they would normally in gas vehicles. However, EV have shorter driving ranges than gas vehicles (van Vliet et al., 2011), and charging time can take multiple hours (Teixeira & Sodré, 2018), which may result in even greater reductions in driving distance compared to using gas vehicles.

3.2 Calculations

The efficacy values for geoengineering proposals, given in Table 1, were converted into Tg per month (Tg/month) from the original values provided by the sources. The sources generally provided values in Pg/year (or Gt/year) (1 Pg = 1 Gt = 10$^{15}$ g), thus, equation (1) was used to convert the values to Tg/month.

\[
\text{Equation 1: } \left(\frac{\text{given value in } P_g/\text{year}}{12 \times 10^{-3}}\right) \times \left(\frac{10^{15} \text{ g}}{1 \text{ Pg}}\right) \times \left(\frac{1 \text{ Tg}}{10^{12} \text{ g}}\right) \times \left(\frac{1 \text{ year}}{12 \text{ months}}\right) = \frac{\text{value in } T_g/\text{month}}{}
\]
No estimates could be found for the average miles driven per month, per private vehicle, globally. A rough estimate, combining data from several sources (see Figure 1), is given by equation (2). Note that this estimate is not intended to be highly accurate; it is meant to provide context and to act as an approximate indicator of the effect switching to electricity-fueled miles could have.

Equation 2: \[ M = \frac{T}{VGY} \]

- \( M \) = average miles/month per vehicle
- \( T \) = total, global private vehicle emissions/year
- \( V \) = total vehicles, globally
- \( G \) = average emissions/mile for gas vehicles
- \( Y \) = 12 months/year

Using the assumptions from section 4.1, equation (3) provides an estimate for the reduction in CO₂ emissions that could be achieved by a reduction of \( X \) gas-fueled miles driven by each private vehicle. \((G - E)\) provides the difference, or reduction, in emissions achieved when one private vehicle drives one mile using electricity instead of gasoline. This value is multiplied by the product of the total number of miles driven times the total number of vehicles being considered, to determine the total reduction in CO₂ emissions. In addition, equation (4) gives an estimate for the reduction in gas-fueled miles required to have the same efficacy as a given geoengineering proposal, where \( R \) equals the efficacy of the given geoengineering proposal.

Equation 3: \[ R = XV(G - E) \]

- \( R \) = reduction in CO₂ emissions
- \( X \) = reduction in gas-fueled miles driven (number of miles driven using only electricity)
- \( V \) = total number of private vehicles
- \( G \) = CO₂ emissions per mile, gas-fueled
- \( E \) = CO₂ emissions per mile (effective), electricity-fueled
* \( E = 0 \) when assuming no emissions, or no distance driven
Equation 4: \( X = \frac{R}{V(G-E)} \)

Same variables as for equation (3).

4. Results

Using the values of 404 grams of CO\(_2\) emitted per mile by gas-fueled vehicles (epa.gov, 2018) and 643 million private vehicles on the road (based on data from oica.net, 2019), equation (3) yields a reduction of 0.260 Tg of CO\(_2\) for every one-mile reduction in miles driven by gas vehicles. Figure 1 provides a visual representation of the efficacy of this individual action relative to estimates for geoengineering proposals. The geoengineering values shown are represented as horizontal lines, for the amount of CO\(_2\) that could be removed from the atmosphere by each proposal over the course of one month. Meanwhile, individual action is represented by the sloped lines, varying with the reduction of \( X \) gas-fueled miles driven. Just as for geoengineering, the reduction \( X \) miles is over the course of one month; and this individual action could be repeated monthly. (To clarify, this value is not compounded. For example, if a person drives an average of 1000 miles/month, and they reduce by \( X = 50 \) miles, their new average would be 950 miles/month, each month. They would not have to then be reduced to 900 miles, then 850 miles, and so forth.) Several lines are shown for individual action, for different emission rates depending on the source of electricity generation.

Figure 1

*Individual action vs. geoengineering*

Comparison of the efficacies of geoengineering proposals with the efficacies of reducing gas-fueled miles driven, globally.
Geoengineering data sources are cited in Table 1. Note that these values are not cumulative; they represent the individual effect each geoengineering proposal could have. CO$_2$ air capture is represented as a dashed line because the value of 3083 Tg/month will likely not be applicable until the year 2100 (Chen & Tavoni, 2013).

E = 0 g/mile: assumes no emissions (using renewable energy) from electricity generation (van Vliet et al., 2011).

E = 10 g/mile: electricity generated from hydroelectric power (Teixeira & Sodré, 2018).

E = 96.3 g/mile: electricity generated from coal (van Vliet et al., 2011).

Average miles/month (1155 miles/month): estimate based on global emissions from private vehicles (Teter et al., 2019), total number of private vehicles (oica.net, 2019), and average emissions per mile (epa.gov, 2018); see equation (2).

Global emissions/month (3000 Tg/month): total CO$_2$ emissions caused by human activities (Ritchie & Roser, 2017).

The required reduction in gas-fueled miles, for the reduction to have the same efficacy as the geoengineering proposals, is given in Table 3. These values are determined using equation (4), where E = 0 g/mile because we are considering a reduction in miles driven in gas vehicles, with no EV or HV replacement.

Table 3

| Geoengineering Proposal | Required reduction in gas-fueled miles |
|-------------------------|----------------------------------------|

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The scenario presented in Figure 1 represents the maximum effect of each geoengineering method and individual action considered, without considering a gradual implementation. Meanwhile, Figure 2 presents two possible paths for implementation of these proposals. These pathways are not intended to be practical deployment guidelines and do not focus on feasibility, current policies, or other factors. Rather, they illustrate the potential of each proposal when deployed at comparable rates (Figure 2(a)) and when EV adoption takes place at a higher rate than geoengineering (Figure 2(b)). We focus on EV adoption as the individual action in these pathways because it has a greater effect than reduced driving does (see section 5.1). The reduction in CO$_2$ from EV adoption is estimated assuming zero emissions from electricity production, using renewable energy (van Vliet et al., 2011). While different sources of electricity generation result in different levels of emissions (Teixeira & Sodré, 2018; van Vliet et al., 2011), a transition to cleaner energy sources alongside EV adoption would contribute to the impact that EV adoption could have.

| Method                          | Effect (t CO$_2$) |
|--------------------------------|-------------------|
| CO$_2$ air capture             | 11868             |
| Afforestation/reforestation    | 3880              |
| BECCS                          | 3207              |
| Enhanced Weathering            | 1282              |
| Biochar                        | 658               |

Figure 2

*Potential pathways of geoengineering and EV deployment*

Geoengineering pathways for both Figures 2(a) and 2(b) estimated assuming maximum deployment is reached in 2050 (data sources are cited in Table 1) and 10% deployment is
reached in 2030 (see Supporting Information). A/R represents afforestation/reforestation; EW represents enhanced weathering. Reduction in emissions for both Figures 2(a) and 2(b) assume zero emissions from electricity generation, using renewable energy (van Vliet et al., 2011), and that the average miles driven is about 1155 miles/month (a rough estimate based on data from Teter et al., 2019; oica.net, 2019; epa.gov, 2018; see equation (2)). In Figure 2(a), global EV adoption follows the same path of deployment as geoengineering, reaching 10% deployment in 2030 and maximum deployment in 2050. Here maximum deployment assumes all private vehicles currently on the road (estimated based on data from oica.net, 2019) are replaced by EV. In Figure 2(b), global EV adoption increases at a rate of 36% per year, following the Sustainable Development Scenario discussed by the IEA (2020). In this pathway, the global EV fleet reaches maximum deployment midway through 2033 (estimated based on data from oica.net, 2019), therefore the total efficacy remains constant after 2033.

Figure 3 compares the cumulative effect of geoengineering and EV deployment with the global carbon budget (GCB) to estimate how much CO$_2$ is unaccounted for in the pathways from Figure 2. The GCB is the total net amount of CO$_2$ that can be emitted while limiting global warming to 1.5°C above pre-industrial levels (Rogelj et al., 2018). Two GCB estimates as of 2020 are presented: 508 Gt and 348 Gt, based on the 2018 GCB (Rogelj et al., 2018) and annual emissions (Ritchie & Roser, 2017), to have a 1/2 and 2/3 chance, respectively, of limiting global warming to 1.5°C (Rogelj et al., 2018). The CO$_2$ that is “unaccounted for” represents the remaining CO$_2$ that will have to be avoided or removed by additional methods in order to stay within these warming limits. This assumes constant emissions of 36 Gt/yr (Ritchie & Roser,
2017) through 2050, which can be reduced through emission cuts to lower the amount of CO₂ that is “unaccounted for.”

Figure 3

Cumulative effects of geoengineering and EV deployment as percentage of cumulative emissions

Total reduction in CO₂ by geoengineering and EV adoption between 2020 and 2050 (based on pathways in Figure 2), compared with global carbon budget (GCB) as of 2020 (based on the 2018 GCB (Rogelj et al., 2018) and annual emissions (Ritchie & Roser, 2017)) and remaining CO₂ emissions that are unaccounted for (assuming constant emissions of 36 Gt/yr (Ritchie & Roser, 2017) through 2050). A/R represents afforestation/reforestation; EW represents enhanced weathering. Figures 3(a) and 3(b) use a GCB that gives a 1/2 chance of limiting global warming to 1.5°C, and Figures 3(c) and 3(d) use a GCB that gives a 2/3 chance (Rogelj et al., 2018). Figures 3(a) and 3(c) follow the pathway outlined in Figure 2(a), in which both geoengineering and EV deployment reach maximum levels in 2050. Figures 3(b) and 3(d) follow the pathway outlined in Figure 2(b), in which EV adoption instead increases by 36% annually (IEA, 2020), reaching maximum deployment in 2033 (based on data from oica.net, 2019), while geoengineering still reaches maximum deployment in 2050.

5. Discussion: individual action or geoengineering?

5.1 Analysis of the results

Considering Figure 1, the effect of individual action could be comparable to geoengineering, if it is taken up on a large-enough scale. The calculations in Table 3 suggest that simply reducing distance traveled in gas vehicles would be insufficient unless a drastic reduction
was made. Replacing gas-fueled vehicles with electricity-fueled vehicles, however, would allow for a more convenient shift with a smaller reduction in miles driven, and would have an important impact compared to those of geoengineering proposals.

Looking more deeply into the data, we conclude that without replacing gas-fueled miles with electricity-fueled miles, the efficacy of simply reducing miles driven is unlikely to be sufficient. This is because, to have the same efficacy as biochar (the least effective geoengineering proposal considered) (Vaughan & Lenton, 2011; cites Lehmann et al., 2006), all private vehicle owners would have to reduce their average driving distance by about 658 miles in one month (see Table 3). To put this in perspective, during the COVID-19 pandemic, gasoline consumption in the United States decreased by about 30% (although this includes other sources of consumption in addition to private vehicles) (Gillingham et al., 2020). 30% of 1155 miles/month is about 347 miles reduced per month, just over one half of the 658 miles/month mentioned above. Another estimate is found by considering that emissions from surface transport (which includes other vehicles in addition to private vehicles) decreased by about 36% during the pandemic (Le Quéré et al., 2020). 36% of 1155 miles/month is about 416 miles reduced per month, less than two thirds the value of the 658 miles/month mentioned previously. While these calculations are only rough estimates of the reduction in miles traveled during the pandemic, they give us a foundation for comparison. In the extreme situation of the COVID-19 pandemic, the reduction in miles was still less than the reduction needed to have the same efficacy as biochar, the least effective geoengineering proposal considered (see Table 1). In order to be comparable to biochar or any of the other geoengineering proposals, the reduction in miles would need to be significantly greater than the reduction due to the pandemic (see Table 3). Even reducing driving by 416 miles/month (the higher estimate of the reduction in miles driven during
the pandemic) corresponds to only a 3.6% reduction in global emissions. As populations begin to return to work, such reductions in miles will not be possible while earning a livelihood.

However, a switch to electricity-fueled miles would allow for a much greater reduction in gas-fueled miles driven because people could still drive the distance they need using electricity. Action to this extent would require all private vehicle owners to switch to EV (or HV, which is not the focus of this section). This would not have to occur immediately; rather, individuals would choose EV instead of gas-fueled vehicles when the time came for them to replace their vehicles anyway. This transition could follow pathways outlined in Figure 2. Once EV and geoengineering reach their maximum deployment, if all miles driven (an estimate of 1155 miles/month, per vehicle, based on data from Teter et al., 2019; epa.gov, 2018; and oica.net, 2019) are replaced with electricity-fueled miles, the reduction in CO₂ emissions ranges from 23% (for coal-generated electricity (van Vliet et al., 2011)) to 30% (for renewable energy (van Vliet et al., 2011)) of the amount of CO₂ removed from the atmosphere by afforestation/reforestation (Crusius, 2020; cites National Academies of Sciences, Engineering, and Medicine, 2019) – which has the highest efficacy of the geoengineering proposals considered (excluding CO₂ air capture for the period until 2050 (Chen & Tavoni, 2013)). However, for enhanced weathering (Strefler et al., 2018), these values range from 69% to 90%, and for biochar (Vaughan & Lenton, 2011; cites Lehmann et al., 2006), they range from 134% to 175% (indicating that, compared to biochar, individual action could actually have greater efficacy). These percentages are considerable enough that individual action should not be ignored as a potential solution to climate change.

Our data also suggest the importance that individual actions could have in both speeding up the path to sufficient CO₂ reduction and in a holistic plan for CO₂ reductions. A comparison
between the scenarios presented in Figure 3 shows that a move to EV by 2050 could be as effective as biochar and almost as effective as enhanced weathering, but would also help reduce the overall unaccounted-for CO\textsubscript{2} that still needs to be dealt with in a holistic solution including one individual action and many forms of geoengineering (Figures 3(a) and 3(c)). A faster move to EV (Figures 3(b) and 3(d)), though likely not as feasible, would be more impactful than biochar and enhanced weathering combined, and almost as impactful as BECCS – a very popular solution in climate models (Rogelj et al., 2018). Further, a faster move to EV would take a larger chunk out of the unaccounted-for CO\textsubscript{2} that even these more holistic solutions leave on the table. There are two important points to take from this. First, a holistic approach with a rapid transition to EV would be an integral piece of efforts to reduce global climate change. This is echoed by a call from the IPCC (2018) that significant emission cuts (45% of 2010 emission levels) are needed by 2030 to limit warming to 1.5°C. Additionally, given the time lag between emissions and global climate effects, the faster the move to reducing emissions, the more impactful this could be (Hansen et al., 2005). Second, this one individual action makes a sizable and important contribution to the reduction in CO\textsubscript{2} emissions, and additional individual actions in conjunction with this holistic solution provide a better chance to fill the gap toward capping global temperature rises at 1.5°C.

5.2 Consequences of geoengineering perceptions

In considering solutions against one another, we see in Figure 1 that CO\textsubscript{2} removal geoengineering is still estimated to be more effective at reducing CO\textsubscript{2} levels in the atmosphere compared to the individual action considered. However, geoengineering poses concerns over the cost and time requirement of large-scale implementation (Caldeira et al., 2013), challenges of global coordination of efforts (including the risk that populations who are underrepresented in
the decision-making process will be disproportionately affected by the drawbacks of geoengineering), and the potential for other, unforeseen consequences (Corner & Pidgeon, 2010). As Trenberth and Dai (2007) warn, “considerable caution should be used regarding any intentional human intervention in the climate system that we do not fully understand.” While Keith (2013) argues that small-scale testing could be used to better understand the consequences before larger-scale deployment occurs, Robock (2008) is concerned that, at least in the case of solar geoengineering, there may be no way to stop the rapid changes in temperature that could result if deployment is stopped or there is rapid cooling due to other causes. Again, as Keith (2013) points out, it is the rate of temperature change, rather than the overall change, that raises more concern for the climate. Additionally, geoengineering only aims to mitigate the effects of emissions on the environment (Caldeira et al., 2013); it does not target the source of emissions (Trenberth & Dai, 2007). The less focus there is on reducing emissions, the more reliance there will have to be on workarounds, such as geoengineering. Because of these drawbacks, geoengineering is often considered to be a “last resort” in the event that other attempts – mainly emission cuts (Fragnière & Gardiner, 2016) – do not succeed (Shepherd, 2009). However, this portrayal of geoengineering as a “safety net” (qtd. in Fragnière & Gardiner, 2016) actually presents its own concerns – not only in how politicians manage climate policies (Dooley & Kartha, 2018), but in how individuals perceive the importance of taking action.

Saving geoengineering for use as a safety net implies that there will come an obvious time to use this last resort (such as when the effects of climate change cannot be undone (Lontzek et al., 2015)). In reality, though, there will be no single, conclusive indication that this moment has been reached; rather, the consequences will take place over time, at different rates (Lontzek et al., 2015). Because these gradual effects are not directly perceived by the public,
more concrete images (such as glacier collapse and endangered or extinct animals) are generally used to warn the public that climate change is a real threat (Hamblyn, 2009). Just as this imagery, these “canaries” (Hamblyn, 2009), present a clear indication of the dangers of climate change, the symbol of geoengineering as a safety net can also act as an indicator of the progression of climate change. However, while numerous canaries have already been presented to the public (Hamblyn, 2009), geoengineering technology has not yet been deployed or even fully developed (Suarez & van Aalst, 2017) (with the exception of some relatively small-scale deployments by CO₂ air capture companies (carbonengineering.com, 2020; climeworks.com, 2020)). While geoengineering could be the alarm that a climate emergency is occurring, prompting individuals to take action, the fact that it has not been deployed poses as a signal that necessary changes, such as emission cuts (Fragnière & Gardiner, 2016), can be postponed. This is particularly concerning in light of analyses of the rhetoric of climate change that suggest that the United States, the country responsible for the 2nd highest CO₂ emissions annually, is prone to perceive climate change as a problem to be solved by scientists and engineers, and not as a moral issue requiring individual action as part of a larger collective (Carvalho, 2007; Hamblyn, 2009). We feel that this makes it especially important to highlight the impacts that individual actions can have and how they measure up (successfully) to geoengineering.

5.3 Conclusion

Considering efficacy alone, it may be concluded from Figures 1 and 3 that both CO₂ removal geoengineering and individual action should be kept in consideration as possible solutions to climate change. While geoengineering – especially afforestation/reforestation (Crusius, 2020; cites National Academies of Sciences, Engineering, and Medicine, 2019) and CO₂ air capture (Chen & Tavoni, 2013) – may be more effective at reducing atmospheric CO₂
levels, individual action should not be overlooked as a viable alternative, particularly if other efforts to reduce emissions on an individual level are considered, such as reducing air travel, household electricity use, meat consumption, and other actions (Jones & Kammen, 2011), in addition to those considered in this paper. Here we selected reducing gas-fueled miles driven as an example of the impact individual changes can have. Reducing gas-fueled miles driven is a particularly powerful individual action, as the ground transportation sector is a major emitter of greenhouse gases, and it is also something that individuals have some control over. While it is likely that after COVID-19, miles driven will increase again, it is also possible that more opportunities to work from home will be made available (BBC Worklife, 2020; Global Workplace Analytics, 2020; Koetsier, 2020). Further, transitioning to electricity-fueled miles is more practical for reducing transportation emissions than changes to other transportation sectors (Mazur et al., 2018). The switch to electric and hybrid vehicles is projected to continue, and analyses of the impacts of this switch in global markets abound (Colmenar-Santos et al., 2019; Kahn Ribeiro et al., 2007; Mazur et al., 2018; Palencia et al., 2017; Saisirirat et al., 2013; van Mierlo & Maggetto, 2007; Zheng et al., 2019). There are certainly opportunities for individuals to make changes to other greenhouse gas emitting sectors, such as use of electricity (27% of emissions by sector, 2018), industry and manufacturing (22%), commercial and residential (12%), and agriculture (10%) via solutions such as reducing use of home and workplace electricity or selecting more renewable energy sources, reducing meat consumption, buying from more sustainably producing companies, etc. (epa.gov, 2020) that we do not highlight here.

While here we offer a comparison of one form of individual action to geoengineering solutions as an example, we note that though a reduction in miles driven is a rather innocuous solution when possible, the adoption of HV and EV is not without problems. Here we calculated
emissions from miles driven using three metrics as an acknowledgment that, in some states in the US, electricity from a “dirty electric grid” could arguably mean electricity-powered vehicles are more polluting than gas-fueled vehicles (Iaconangelo, 2020). While it is hoped that this is remedied by cleaner grids across the US in the near future, a global plan considering other individual actions in addition to altering miles driven would likely yield the best results.

Indeed, the most promising solution to climate change is making significant emission cuts (Fragnière & Gardiner, 2016), and emission cuts by individuals are a component of this. Currently, human activities cause a total of 36 Gt of CO₂ emissions per month (Ritchie & Roser, 2017), and driving private vehicles accounts for approximately 10% of these emissions (based on data from Teter et al., 2019; Ritchie & Roser, 2017). Meanwhile, if the maximum effects of all the geoengineering proposals considered in Table 1 (excluding CO₂ air capture for reasons mentioned previously) are added, their combined reduction of CO₂ is only 78% of total human emissions. However, it is highly unlikely that all of these geoengineering proposals would operate at their maximum potential, or even be in use, at the same time (Lawrence et al., 2018); in a realistic scenario, the combined efficacy of geoengineering proposals would be even lower than 78% of total human emissions. As illustrated in Figure 3, less than a quarter of CO₂ emissions from 2020 to 2050 would actually be removed by geoengineering if deployment follows the pathways outlined in Figure 2. Meanwhile, having close to net-zero emissions is a key component of the climate’s stability (Keith & Irvine, 2016), and net-zero emissions needs to be achieved around 2050 in order to comply with the goal of keeping post-industrial warming within 1.5°C (IPCC, 2018). (Since CO₂ air capture is unlikely to be deployed on a global scale before 2065 (Chen & Tavoni, 2013), its effects cannot be relied on to significantly reduce atmospheric CO₂ concentrations before 2050.) Thus, if or when geoengineering is deployed, it
will still need to be supplemented by emission cuts in the near future, before 2050. As Figure 3 demonstrates, a significant portion of these emission cuts can come from the transition to EV.

It may be argued that adopting individual action on a global scale, so its effect is comparable to that of geoengineering, is a prohibitively high target. However, geoengineering itself would also require global-scale adoption (generally at high financial cost) (Caldeira et al., 2013), involving significant coordination among countries and citizens (Corner & Pidgeon, 2010). Instead, these efforts could be focused on reducing emissions, not only at an industrial level but also at an individual level as argued in this paper. Even if geoengineering is deployed as a safeguard (with the hopes of global emission reductions), there remains the concern that the role of geoengineering as a “safety net” (qtd. in Fragnière & Gardiner, 2016) may enable individual complacency. (Robock, 2008, and Keith, 2013, from opposite sides of the debate on whether to deploy geoengineering, agree that geoengineering has the potential to reduce motivation to cut emissions.) If geoengineering is to be relied on as a safeguard, though, there is still an opportunity to alter how it is framed. Emphasizing why geoengineering is the “last resort,” not the first choice (Shepherd, 2009), may allow geoengineering to be used as a tool to encourage individual action. By focusing on the drawbacks of geoengineering in its role as a safeguard, this may motivate individuals to adopt individual action rather than be faced with the potential consequences of geoengineering. While a “both-and” holistic approach that includes geoengineering and individual actions will likely be necessary to remove existing CO$_2$ from the atmosphere, and to reduce continuing emissions, a rekindling of the role individuals can play is necessary to reinvigorate public motivation to take action.

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